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Report of the Study Group on Risk Assessment and Management Advice (SGRAMA)

18–21 April 2006

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Contents

Executive summary

The ICES Study Group on Risk Assessment and Management Advice (SGRAMA) met in Copenhagen 18–21 April 2006. The Study Group started its work by reviewing different approaches to risk assessment and focused on differences in the structural approach (the risk assessment framework). The Study Group has also started the work of identifying components of an ICES risk assessment framework. The work is a part of the group's terms of reference a) and b). Terms of reference c) and d) have not been considered.

Most approaches to risk assessment describe risk identification and risk estimation as two major components of a risk assessment framework. The Study Group will continue the review of different approaches and also focus on the importance of communication with managers and stakeholders. Communication will be essential in establishing the context or settings within which a risk assessment is produced, and will essential in creating a common understanding (also for the results of an assessment).

The Study Group needs more participants with backgrounds from ecology, fisheries system and ecosystem effects of fishing activities. Risk assessments are multi-disciplinary and have the potential of bringing elements of ecosystem approach into fisheries advice.

1 Opening of the meeting

The meeting opened on 18 April 2006 at 14:30. The late start was due to the late arrival of some of the members of the group because of flight delays. That left the Study Group with effectively three days for the meeting. The meeting opened with five of the approximately 10 nominated members.

2 Adoption of the agenda

The Study Group decided to not adopt a formal agenda, but choose to start the work by reviewing work within the field of risk assessment (see Sections 4.1–4.7) and build the report up around our the review process. Two working documents were presented to the Study Group. The first was titled “A rebuilding framework for an optimal control of multispecies, multistock, and/or multiarea fisheries”. The second working document was submitted by email and gave an example on estimating model uncertainty by varying some settings in FLXSA for North Sea Haddock.

3 Introduction

“Scientific training leaves us with an unreasonable preoccupation with best estimates of variables.” (Burgmann, 2005)

The concept of risk is not unfamiliar within ICES and is usually used as the probability of some negative event or harm. A quick search through some ICES working group reports revealed a few examples of how the word is used: “ [...] combine high long term yield with low risk relative to limit reference points”, “[...] being at risk of reduced reproductive capacity” and even “[...] lower risk of fishing outside precautionary limits”.

This Study Group is ICES first step in establishing guidelines for producing risk assessments and the inclusion of such information in advice to managers. Such information will help managers to manage risk in fisheries. The field covered is close to the fields of SGMAS and risk management should be considered a part of management strategies. The success of the Study Group will depend on contributions of expertise from many disciplines within ICES including among others understanding how fisheries systems work, multispecies effects and ecosystem effects of fishing.

The establishing of a context within which to produce a risk assessment and to communicate the results from such an assessment will depend more on communication with managers and stakeholders than in the traditional fisheries advice. The implementation of risk assessment as a basis for advice to managers will depend on “a new culture of communication”.

Please note that this report represents initial work with limited participation and time.

4 Reviews

This chapter consists of two well-differentiated parts. On the first part the main ideas about risk terminology and decision-making framework of some relevant works are summarized. This covers general books as Burgmann (2004) or reports from organizations like UKCIP (Willows and Connell 2004), IPCC (2004) or EPA (1998) or published papers as (Lane and Stephenson 1997; Francis and Shotton 1997). In addition, different fields like climate change adaptation in (IPCC 2004; Willows and Connell 2004), environmental management in Burgmann (2004) and EPA (1998) or fisheries management in Lane and Stephenson (1997) and Francis and Shotton (1997) are dealt with, providing a broad perspective throughout the applications in different fields. The second part studies the main similarities and discrepancies of the reviewed literature, with a special attention to uncertainty, risk terminology and decision making framework.

It is important to note that this section does not intend to be a complete revision of the available literature, but only a few examples of different ways for defining and dealing with risk related issues.

The Study Group should continue the review process at the next meeting. One candidate for the review process is Standards Australia (2004 a; 2004b) together with examples of how this framework has been applied within fisheries systems. Other relevant examples/approaches should also be considered for revision.

4.1 Review of IPCC Workshop on "Describing Scientific Uncertainties in Climate Change to Support Analysis of Risk and of Options" (IPCC, 2004)

The reviewed document from Intergovernmental Panel on Climate Change (IPCC, 2004) is a report from a workshop and presents risk and uncertainty from several angles. The main issue is uncertainty rather than risk: uncertainty related to science and socio-economic factors but also communication of uncertainty is emphasized. The workshop conclusions are more recommendations for future work within IPCC on uncertainty and risk so that it does not conclude on any framework for risk assessment or risk management. However there are some elements from this report that is worth noting. One is a presentation of the UKCIP approach, which is reviewed in Section 4.4. We will thus concentrate on the workshop's recommendations on how to handle uncertainty questions and some considerations on risk that are presented in different parts of the report.

Workshop recommendations

One of the conclusions at the workshop was a list of recommendations on how to handle uncertainty questions. These were:

- Authors should consider how to deal with uncertainty early on in their planning.
- Key issues requiring careful treatment of uncertainties should be identified as soon as possible.
- Consistency across the report should be maintained by using techniques for communicating uncertainty from among a set of options summarized in the guidance notes.
- Authors should consider both structural and statistical sources of uncertainty
- Authors should note the difference between likelihood and level of confidence in the underlying science.
- Probability distributions should only be used where there is high confidence in the underlying science.
- Traceable accounts should document the basis used for making expert judgment.

Risk

The goal of the workshop was not to agree on a risk framework, but frameworks are presented in papers at the workshop. The report shows that there is an agreement from 1998 on how to use the term "risk": "the likelihood that some event will occur or its expected frequency of occurring and the magnitude of the consequences of that event".

The report recognizes that there are a number of different approaches to assessing risk, from formal and quantitative to largely personal responses based on experience and perceptions. All these deal with uncertainty in one way or another and the qualitative and contextual aspects are always important. For example, asymmetry is often recognized in the sense that being wrong in one direction may have more serious consequences than being wrong in the other.

The report says that an aim is to enable users of the IPCC assessments to more easily relate effects of climate change to other risks, and to integrate decision on climate change with existing decision making frameworks for dealing with risks.

Further the report argues that it is important to distinguish between uncertainties in predicting the frequencies of events and the uncertainty in their consequences.

This is an example of how it links risk to uncertainty: "Probabilistic approaches can be applied to risk analysis when strict numeric probabilities can be defined, e.g. when long term statistics are available for stationary phenomena. Because of this, risk analysis is most easily linked to probabilistic approaches to uncertainty. However, risk analysis techniques are frequently adapted to deal with circumstances in which strict numeric probabilities cannot be defined. In either case, uncertainty analysis plays a key role in risk assessment."

Uncertainty aspects (selected)

In the report it is highlighted that there is a difference between the level of uncertainty and the level of confidence. By the level of uncertainty they mean the quantified uncertainty while the level of confidence refers to the degree of belief or confidence in a science community that available models or analyses are accurate. The confidence is based on both evidence and the more subjective interpretation of results. The report argues that both the quantified uncertainty and the confidence should be stated.

It is expressed that rather than presenting the single most likely prediction, a range of possible outcomes should be presented.

It is recommended that a comprehensive view of all plausible sources of uncertainty should be presented.

The report suggests how to present the knowledge that climate assessments are based on to reflect uncertainty aspects:

- Known: summarize present knowledge;
- Unknown: describe research needed to improve that knowledge;
- Unknowable: summarize what we are unlikely to be able to know before the changes actually occur.

The report presents an interesting view on the nature of uncertainty:

"The goal of making scientific understanding of climate change widely accessible raises particular challenges when it comes to dealing with uncertainty. Uncertainties are usually more difficult to quantify than the factors to which they apply; their treatment is more complex both conceptually and operationally; and the normal use of language to describe uncertainty is often ambiguous. In order to deal with uncertainty in a way that is coherent [...] and useful for decision making it is recommended that descriptions of uncertainty be designed in ways that will improve risk assessment. This approach recognizes that climate change will modify existing risks and in doing so introduce additional sources of uncertainty into risk assessment."

4.2 Review of "Guidelines for Ecological Risk Assessment" (EPA 1998)

The document has 188 pages and has in addition to the sections related to risk assessment also a section on "response to science advisory board and public documents". This very brief review is looking into some of the terminology and how the assessment process is described (as a framework).

Terminology

The guidelines document has a separate appendix on “key terms” and four of those are shown below:

Assessment endpoint – An explicit expression of the environmental value that is to be protected, operationally defined by an ecological entity and its attributes. For example, salmon are valued ecological entities; reproduction and age class structure are some of their important attributes. Together “salmon reproduction and age class structure” form an assessment endpoint.

Conceptual model – A conceptual model in problem formulation is a written description and visual representation of predicted relationships between ecological entities and the stressors to which they may be exposed.

Ecological risk assessment – The process that evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors.

Risk characterization – A phase of ecological risk assessment that integrates the exposure and stressor response profiles to evaluate the likelihood of adverse ecological effects associated with exposure to a stressor. Lines of evidence and the adversity of effects are discussed.

The guidelines contain no clear definition of risk as such. And since the guidelines are intended as internal guidance for EPA (U.S. Environmental Protection Agency) they are written with a specific set of problems in mind and much of the terminology is likely to exist as a part of an “agency culture”.

Framework

The guidelines describe the risk assessment process as three phases: Problem formulation, analysis and risk characterization.

1) The purpose of the problem formulation phase is to articulate the problems (risks?) assessed and to plan how to do the next two phases (analysis and characterization). Initial work includes the “integration” of available information used to produce “assessment endpoints” and “conceptual models”.

2) The “assessment endpoints” and “conceptual models” are used to direct the analysis (second phase). The analysis is focused on “characterization of exposure” and “characterization of ecological effects” (cause and effect).

3) The risk characterization phase is divided into “risk estimation” and “risk description”. The risk estimation part gives fairly practical advice on how to estimate risk including the use of professional judgment or other qualitative evaluation.

The guidelines include some considerations related to risk management, risk managers and “interested parties”. The guidelines state that the planning of a risk assessment should include dialogue with risk managers and “interested parties“. “Communicating results to the risk manager” is mentioned as a separate step after risk assessment. “The ecological risk assessment framework” is visualised in Figure 4.2.1 (from EPA 1998)

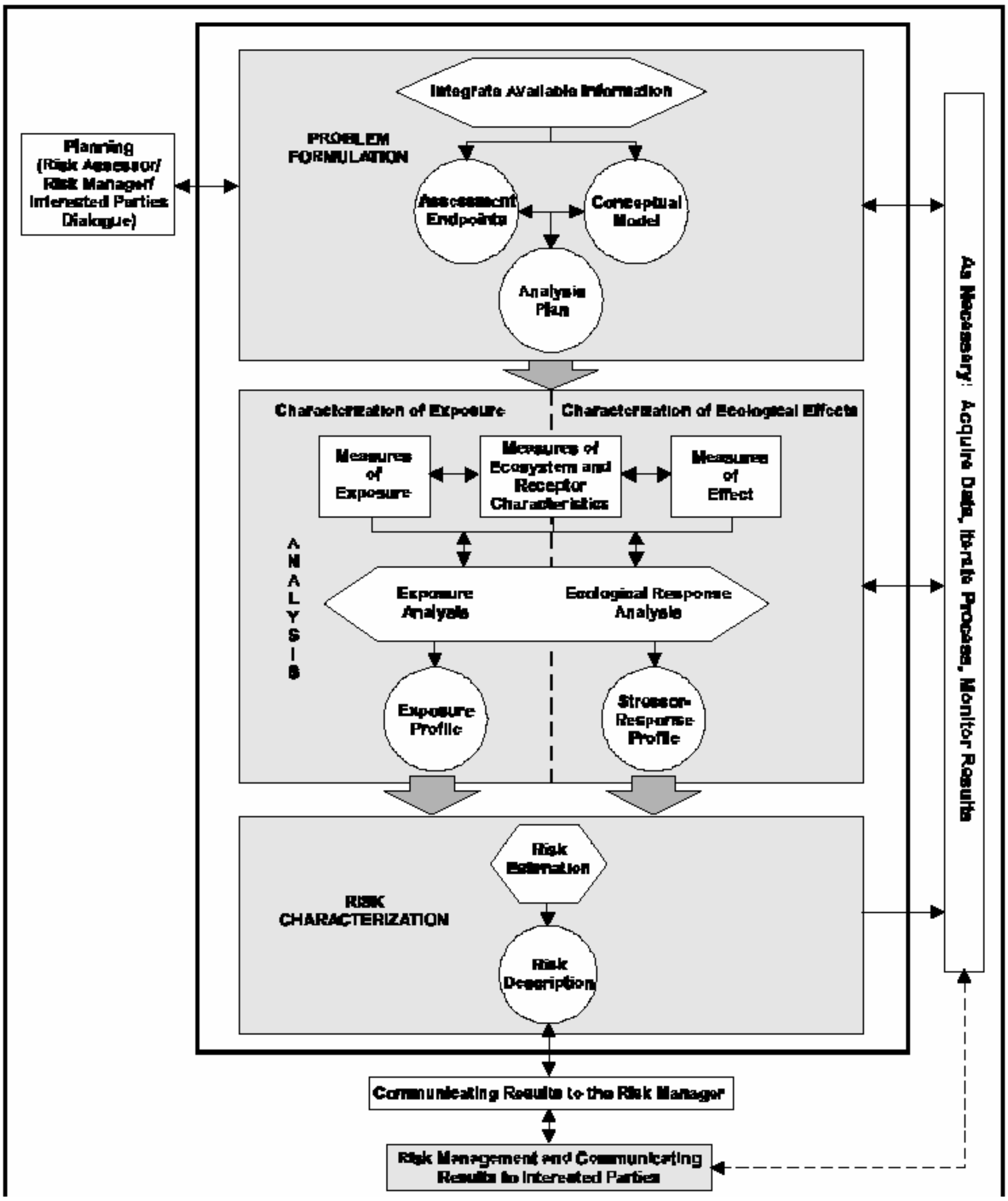

Figure 4.2.1: The ecological risk assessment framework (from EPA, 1998).

4.3 Review of the book "Risks and Decisions for Conservation and Environmental Management" (Burgmann, 2004)

This review is limited to aspects of risk assessment and/or risk management frameworks (relevant chapters are 3, 5 and 12).

Overview and overall impression

This book outlines how to conduct a complete environmental risk assessment. The first part documents the psychology and philosophy of risk perception and assessment, introducing a taxonomy of uncertainty and the importance of context; it provides a critical examination of the use and abuse of expert judgement and goes on to outline approaches to hazard identification and subjective ranking that account for uncertainty and context.

The second part of the book describes technical tools that can help risk assessments to be transparent and internally consistent; these include interval arithmetic, ecotoxicological methods, logic trees and Monte Carlo simulation. These methods have an established place in risk assessments in many disciplines and their strengths and weaknesses are explored. The last part of the book outlines some new approaches, including p-bounds and information-gap theory, and describes how quantitative and subjective assessments can be used to make transparent decisions.

The book thus covers a broad field of aspects regarding risk assessment and management for the decision making process in conservation biology. This is also reflected in the table of contents given below:

1) Values, history and perception
2) Kinds of uncertainty
3) Conventions and risk management cycle
4) Experts, stakeholders and elicitation
5) Conceptual models and hazard assessment
6) Risk ranking
7) Ecotoxicology
8) Logic trees and decisions
9) Interval arithmetic
10) Monte Carlo
11) Inference, decisions, monitoring and updating
12) Decisions and risk management

From this it can be seen that only part of the chapters are directly related to assessment and management procedures/algorithms and thus may have some potential for setting up a template of a risk assessment and/or management framework. The chapters directly touching these three aspects are 3, 5, and 12. Because of their introductory nature also chapters 1 and 2 will be part of the review.

In general, as the table of contents shows this book is quite complete in spanning a broad range of aspects in environmental risk assessment and management. It thus gives a lot of definitions of all-important elements of risk assessment and management. Unfortunately it is predominately descriptive and thus dominated by phrasing definitions and procedures and less by comprehensively formulating these in some formal way using a statistical or mathematical language where it would be necessary. But as outlined in the preface of the book this was also not the intention of it. It further lacks detailed examples where equations are given to a somewhat sufficient extent; the only chapter where some examples with equations are given is chapter 10 (“Monte Carlo”). Anyhow, a strength of the book is that (also in chapter 10) sensitivity analysis is outlined here as a powerful tool to check underlying model assumptions by examining uncertainties (parameter uncertainty, structural uncertainty, shape uncertainty, dependency uncertainty). A weakness of the book is that the author jumps between the various fields in a non-structured way.

In summary, it is a good book for giving a complete descriptive overview of the topic. Anyway, for practically installing and implementing a risk based assessment and management approach within ICES we need clearer and more explicit definitions and formulations in order to make a step forward compared to the current status quo. The book has more the character of a bulky philosophical encyclopaedia and less of a systematically structured manual how to proceed. In practice it lacks the instructional ability necessary for creating a risk assessment and management framework. Nevertheless, to some degree it can be a good source for looking up specific things (e.g. definitions, concepts) and clarifying these.

Chapters 1 and 2: Introduction and basic definitions

Risk is described here, as "the chance, within a time frame, of an adverse event with specific consequences". The term “hazard” is used as a part of the detailed risk definition where hazard itself is defined as an intrinsic potential of harm.

Risk analysis is defined as "evaluation and communication of the nature and extent of uncertainty".

Risk assessment is understood as the "completion of all stages of the risk management cycle, a marriage of risk analysis, adaptive management, decision tools, monitoring and validation".

What is good here is that it outlines the duality of probability by distinguishing between chance and belief; the one dimension of probability is seen here as a statistical (or relative) frequency (objective probability, chance), the second dimension as the degree of belief warranted by evidence (subjective probability). It then presents a variety of probability definitions in this context that could effect risk measurement and stresses the fact that the concepts of probability and of defining consequence play a major role in risk definition and estimation.

It also makes the connection between probability and statistical inference and consequently outlines the link to uncertainty; in an own chapter (chapter 2) it thus describes the various types of sources influencing uncertainty (epistemic uncertainty: variability, measurement error, systematic error, natural variation, model uncertainty, subjective judgement; linguistic uncertainty: vagueness, context dependence, ambiguity, underspecification, indeterminacy).

Chapter 3: Conventions and the Risk Management Cycle

This chapter focuses on defining some essential conventions (hazard, stressors, environmental aspects, environmental effects) and on giving a rough overview of various disciplines (in terms of selected examples which illustrates aspects of risk assessment procedures) and some risk definitions (probability interpretation, frequency interpretation, subjective ranking) related to these such as

- ecology (fisheries, conservation biology)
- engineering (nuclear power, petroleum geology)
- ecotoxicology (for instance, US EPA)
- public health (physician's judgements, epidemiology, US, UK)
- economics (stock market mechanisms).

It sets up a common context for environmental risk assessment by defining

- management goals (that embody broad objectives)
- assessment endpoints (that translate management goals into a conceptual model)
- measurement endpoints (things that can be actually measured)

and by touching following two aspects

- selecting endpoints (difficult to do due to complexity of systems, definition of general characteristics, tools to test whether objectives are reached)
- targeting risk assessments
    - sampling ecosystem attributes, indicators
    - definition of the level of impact (populations, single/multiple species, communities, ecological processes, natural resources)
    - measures of impact (changes in genetic variability within/between populations, relative abundance of stage/of a species, numbers of species and their relative abundances, the abundances of functionally different kinds

of organisms, species turnover from place to place in the landscape within a community, the value or magnitude of ecosystem services, species turnover among communities, the number/size/spatial distribution of communities).

Other aspects touched are practicalities for the choice of measure such as expense and time, experience in labs, problems with the definition of endpoints, complexity of systems, the need of calibration/standardization/standards (baseline conditions) and of setting up protocols, visualisation tools, etc.

It then discusses the risk management cycle, which involves the steps

- initial learning
- problem formulation
- hazard identification
- risk analysis
- sensitivity analysis
- decision-making
- monitoring
- communicating
- updating
- plus from-time-to-time validation, revision, reinforcement, adaptive improvement

Chapter 5: Conceptual Models and Hazard Measurement

Here conceptual models of hazard assessment are discussed with focus on schematically structuring and framing it. The simplest and most illustrative one is considered to be an influence diagram which is basically a visual representation of the functional components and dependencies in the system with different types of shapes (ellipses, rectangles) representing variables, data, and parameters. Arrows link the elements to specify causal relationships and dependencies.

It is further stated that – "to make things clearer and to foster a feasibility/operability study – proposals should be separated into phases (time frame) and should include a benefit-cost (investment) analysis." This chapter then discusses how to set up checklists, carrying out (structured) brainstorming (expert brainstorming, hazard operability analysis (HAZOP)), and formulating a hazard matrix as a matrix of interactions linking hazards to activities and components of the environment that may be affected by the actions.

It also touches FMEA, which is the failure modes (categories of failure) and effect analysis. It involves calculating a risk priority number (RPN) for each hazard as the product of the three quantities severity (assessment of the seriousness of the effect of failure), occurrence (assessment of the likelihood that a particular cause will lead to a failure mode during a specific time frame) and detection (assessment of the likelihood that the current controls will detect the cause of failure mode or the failure mode itself). The RPN is used to set priorities for action on hazards and to identify elements that require additional planning and to set critical thresholds.

Then another method is discussed which is the hierarchical holographic modelling (HHM). Hierarchical holographic models recognize that more than one conceptual (or mathematical) model is possible for any system. They try to capture intuition and perspectives embodied in different conceptual (or mathematical) models/sub models (i.e. individual assumptions, biases, etc. of some specific modeller). Each sub model is then seen to be a complete view of the system from a single perspective.

Chapter 12: Decisions and Risk Management

It is firstly stated here that risk management makes use of the results and insights from risk assessment to manage the environment. Chapter 12 touches following aspects

- the link between policy and risk (comparative risks, real and perceived risks, definition of acceptable risks);
- the philosophy of strategic decisions (decision criteria, risk regulation, procedures of deciding under uncertainty);
- the philosophy of stochastic analyses and decisions (stochastic dominance, benefit-cost analysis, stochastic dynamic programming);
- what to do with info-gaps (measures of performance, models for uncertainty);
- how to evaluate attitudes to decisions (scenario analyses, multi-criteria decision analyses, multi-criteria mapping);
- how to communicate risks (communicating probabilities/comparative risks, selection of the target audience and adaptation to it, determination of the purpose of communication, meeting legal requirements or policies limiting the design of risk communication);
- the philosophy of adaptive management, precaution and stakeholder involvement.

4.4 Review of the UKCIP Technical Report on "Climate adaptation: risk, uncertainty and decision making" (Willows and Connell, 2003)

The technical report of the United Kingdom Climate Impacts Programme (UKCIP) (Willows and Connell, 2003) aims at providing guidance that helps decision and policy makers to take into account the risk and uncertainty associated with climate variability and future climate change and to identify and evaluate measures to mitigate the impact or exploit the opportunities presented by future climate. The report is structured in two parts. The first part presents a decision-making framework. The second part provides supporting material on risk assessment in general and risk-based climate change impact assessments in particular, including an overview of concepts related to risk and uncertainty.

Terminology

The basic definitions related to risk and uncertainty that are given in the report are as follows:

Hazard: Situation or event with the potential to cause harm.

Risk: Product of the probability or likelihood of an event occurring and the magnitude of the impact or consequence associated to that event. The reports remarks that in some cases in might be more useful to retain and communicate the likelihood and impact components of risk separately, as this will allow the decision-maker to decide policy and ethical issues. For example, if the decision-maker may wish to implement a policy of risk-aversion.

Uncertainty: Lack of knowledge. Thus, concerning risk uncertainty may result when the probabilities of the hazards and/or the magnitudes of their associated consequences are uncertain. However, even when there is a precise knowledge of these components there is still uncertainty because outcomes are determined probabilistically.

Three types of uncertainty are distinguished:

a) Natural variability

b) Data uncertainty arising from measurement error, incomplete or insufficient data or extrapolated data.

c) Knowledge uncertainty referring to lack of knowledge about the processes or future outcomes. Model uncertainty is a particular case of knowledge uncertainty and includes uncertainty on model choice and structure; model input values, model parameters and model output variables.

Risk analysis: Process, by which knowledge concerning the probabilities, uncertainties and magnitude of future events is brought together, analysed and organised by the decision-maker. Risk analysis includes risk assessment, risk evaluation, and the identification and assessment of risk management alternatives.

Risk identification: Process by which hazards are recognized and characterized.

Risk assessment: Process by which hazards and consequences are identified, characterized as to their probability and magnitude, and their significance assessed. Risk assessment may involve either quantitative or qualitative techniques. Qualitative techniques are particularly useful in circumstances where we lack knowledge of the probabilities.

Risk evaluation: Component of risk assessment in which judgments are made about the significance and acceptability of risk.

Risk estimation: Rigorous determination of the characteristics of risks, usually progressing from qualitative to more quantitative approaches. These characteristics include the magnitude, spatial scale, duration and intensity of adverse consequences and their associated probabilities as well as a description of the cause and effect link.

Risk screening: Following initial identification of hazards and risks, risk screening is the process by which it is determined which risks should be investigated in more detail. Risk screening is usually based on ranking or scoring methods

Risk assessment endpoints: Explicit expression of the attributes, associated with a receptor that is to be protected or achieved. Risk assessment endpoints may represent an intrinsic threshold or an agreed, policy-defined threshold, at which decisions to manage the risk will be required. A measurement endpoint may be defined for the attribute in terms of the probability that a certain level of performance will be achieved over a defined period of time, and with a specified level of confidence.

Risk management: Any action or portfolio of actions that aim to reduce the probability and magnitude of unwanted consequences or manage the consequences of realized risks.

Tolerable risk: The willingness to live with a particular level of risk, in return for certain benefits, based upon a certain confidence that the risk is being properly controlled or managed.

Decision making framework

The decision-making framework is illustrated in Figure 4.4.1.

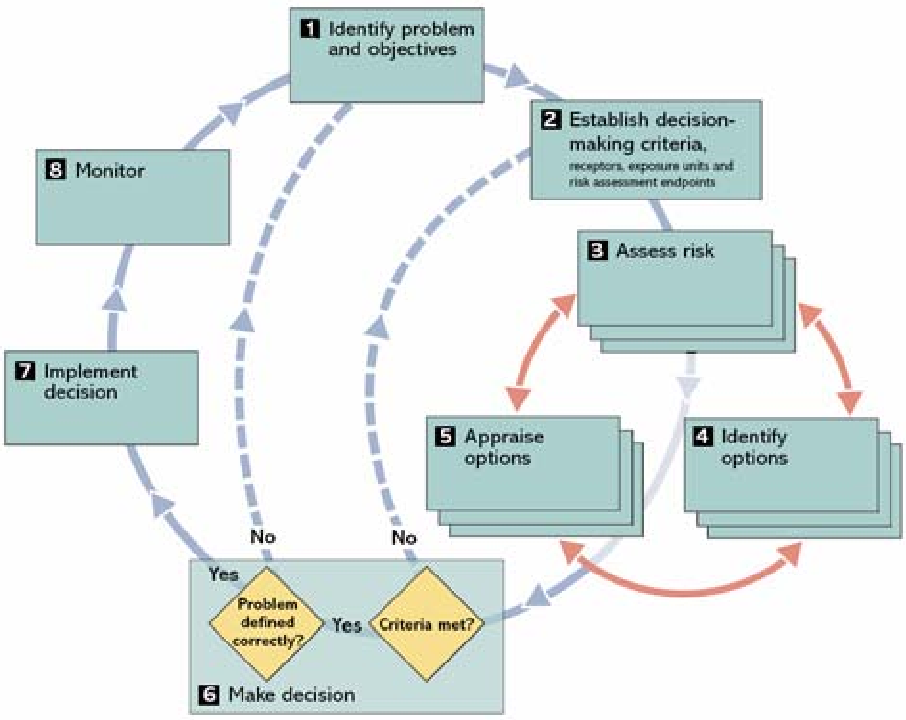

Figure 4.4.1: D Decision making framework taken from the UKCIP report (Willows and Connell 2003).

The decision-making framework has eight stages:

1) Identify problem and objectives: Before starting the decision making process it is important to understand the reasons for the decision being made and the decision-maker's broad objectives.

2) Establish decision-making criteria: In this stage the broad objectives of the decision-maker of the previous stage need to be translated into operational criteria that can be used in a formal risk assessment, and against which the performance of different options and the subsequent decision can be evaluated. This includes an agreement on preliminary risk assessment endpoints that relate to the decision criteria.

3) Assess risk. The objectives of this stage are to characterise the nature of the risk, to provide qualitative or quantitative estimates of the risk, to assess the consequences of uncertainty for decision options and to compare sources of risk. One of the key issues of this framework is that the risk assessment will be undertaken at different levels depending on the level of decision and the level of understanding. See Figure 4.4.2.

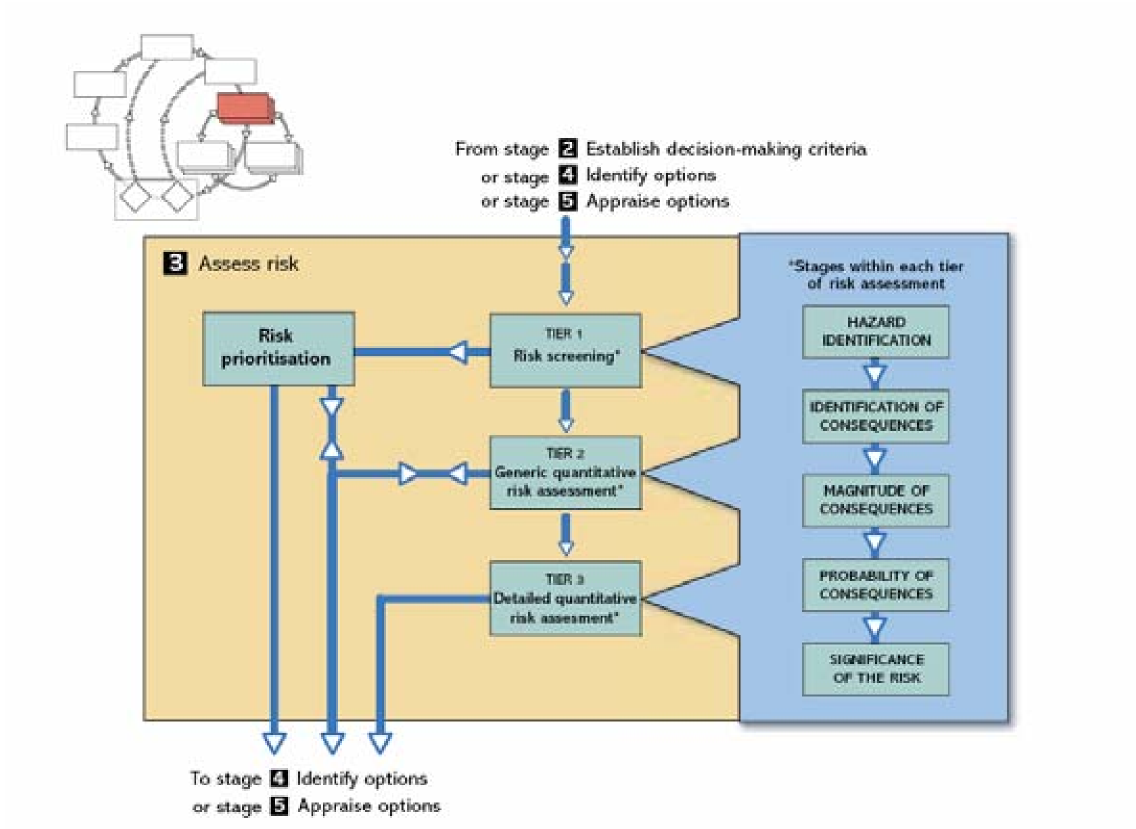

Figure 4.4.2: S Stages within risk assessment (Willows and Connell, 2003).

4) Identify options: At this stage it is important to consider a wide range of potential options and to avoid the premature rejection of viable options.

5) Appraise options: This stage comprises the evaluation of the options against the criteria established in stage 2.

6) Make decision: This stage consists on bringing the information together and evaluating it against the objectives and defined decision criteria. It includes the effective communication of the analysis.

7) Implement decision.

8) Monitor, evaluate and review.

In general, the three important aspects of this framework are that: (i) it is circular, allowing the performance to be reviewed and decisions revisited through time, (ii) it is iterative, allowing refinement as a result of previous analyses and (iii) certain stages are tiered, allowing screening, evaluation and prioritisation of risks. It is important to remark that this decision process should involve all stakeholders.

4.5 Review of the paper "A framework for risk analysis in fisheries decision-making" (Lane and Stephenson, 1998)

This paper examines the form and content of an analysis for decision-making that specifically incorporates risk analysis – risk assessment as well as risk management.

Terminology

The main definitions related to risk that are given in Lane and Stephenson (1998) is as follows:

Risk analysis: Overall process that comprises risk assessment and risk management

Risk assessment: Process that evaluates possible outcomes or consequences and estimates their likelihood of occurrence as a function of a decision taken and the probabilistic realization of the uncontrollable state dynamics of the system.

Risk management: Process whereby decision makers use information from risk assessment to evaluate and compare decision alternatives.

Framework

The authors state that in the traditional framework for fisheries advice (Figure 4.5.1) the scientific resource evaluation function is restricted to biological considerations and it is separated from other economical or social issues. However, afterwards these other factors will lead to modification of advice by external pressures (kinked lines).

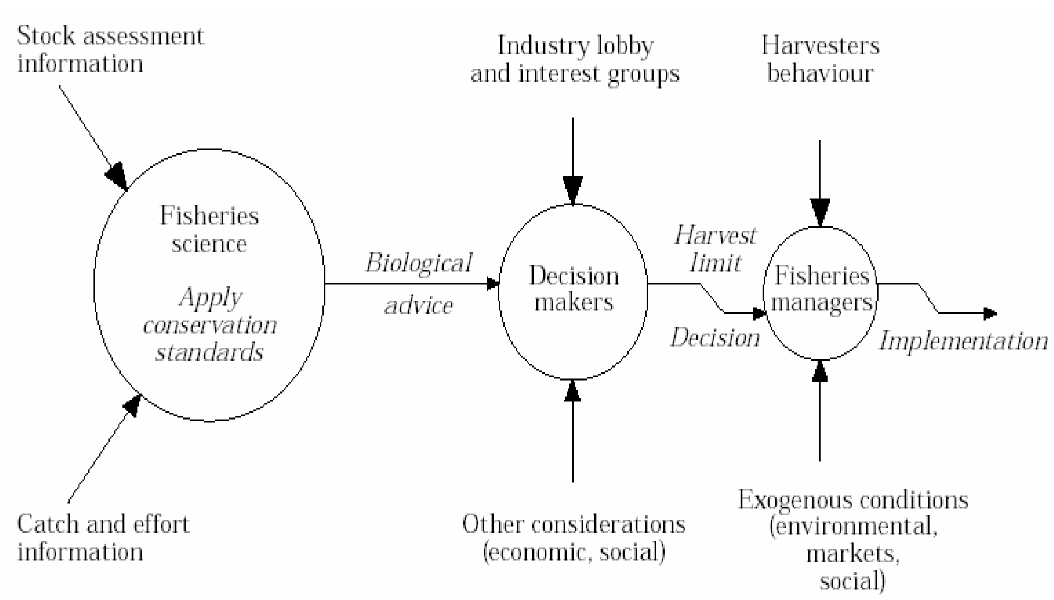

Figure 4.5.1: Conceptual view of the traditional framework for fisheries advice and management (Lane and Stephenson, 1995a).

Hence, the authors defend that effective decision-making in fisheries requires the provision of ‘‘fisheries management advice’’ (vs. strictly biological advice or economic advice, etc.) based on applying general principles of problem-solving including quantitative evaluation of alternatives and projection of their strategic implications on all aspects of the fishery system. The proposed decision framework is illustrated in Figure 4.5.2. The essential steps in this framework are summarized as follows:

1) Problem definition: definition of the problem includes quantification of objectives and constraints for the fishery system.

2) Deterministic modelling: this component includes scenario development, the projection of controllable and uncontrollable variables affecting the fishery system (e.g. market evolution, price and cost adjustments) and preliminary deterministic modelling of the multidimensional impacts of all management options.

3) Simulation modelling: the simulation results are organized to provide the likelihood of decision performance under stochastically varying conditions, e.g. variable stock recruitment and growth, varying economic conditions, etc.

4) Risk analysis part I (risk assessment): this component compiles the distribution of performance measures resulting from the simulation model and assigns

probabilities to the multidimensional simulation outcomes for each decision alternative.

5) Risk analysis part II (risk management): this component is the application of decision-making criteria embodied in management utility functions that measure the expected value of each decision alternative in terms of the multiple criteria and their trade-offs, and thereby evaluates and ranks alternative decisions for presentation to decision makers.

6) Implementation and monitoring: The final step in the problem-solving process is the implementation of the decision. These steps form an integrated and interdependent decision analysis framework with continual feedback as illustrated in the diagram of Figure 2. The circular process contrasts with the linear framework of Figure 1 and embodies the feedback loop of successive decisions made by the responsible political powers on the integrated advice developed from all relevant components of the fishery and implemented into fisheries operations. Risk assessment is an integral part of the advice development stage where multiple alternatives and their attributes are presented as part of the provision of advice. Risk management advice is provided to the decision-makers as the basis for their ultimate course of action.

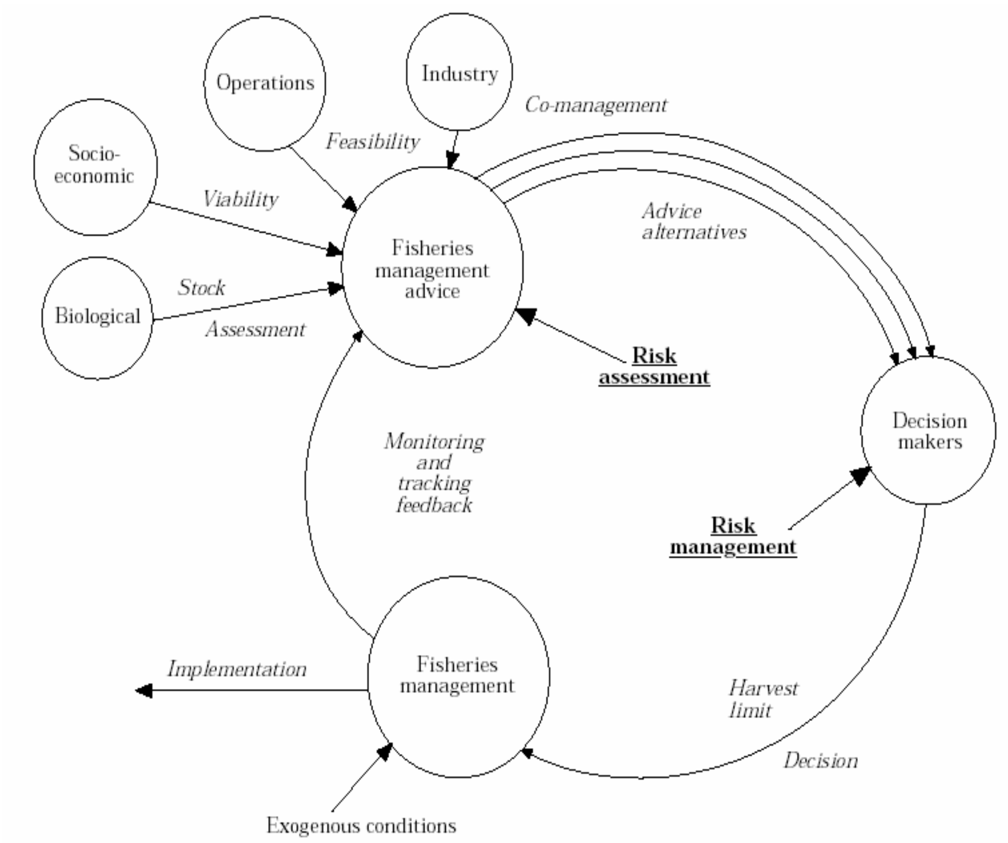

Figure 4.5.2: Conceptual view of the proposed decision analysis framework for fisheries management including risk assessment and risk management components (Lane and Stephenson, 1995a).

4.6 Review of the paper ""Risk" in fisheries management" (Francis and Shotton, 1997)

The paper by Francis and Shotton (1997) provides a complete review of both the terminology and the process of dealing with risk that includes risk assessment and risk management.

Terminology

Uncertainty

The paper uses the definition of uncertainty given by FAO (1995) "The incompleteness of knowledge about the state or processes (past, present, and future) of nature") and distinguishes six types of uncertainty: those associated with process, observation, model, estimation, implementation, and institutions.

Risk

The paper presents the two different ways of defining risk. The first one is as "the probability of something undesirable happening" and the second one as the probability of undesirable events and the magnitude of the associated consequences.

Risk assessment

Although in the review a variety of definitions that use different name conventions are presented, all of them agree on that risk assessment is "using information on the status and dynamics of the fishery to present fishery managers with probabilistic descriptions of the likely effects of alternative future management options."

Risk management

Similarly to risk assessment, a large number of definitions have been given to risk management. However, the authors defend that "risk management entails a description of the decision criteria that is sufficiently complete and specific to define the quantities that should be calculated in the risk assessment and to make the decision".

Framework

In this paper the framework for dealing with risk has two stages: risk assessment and risk management.

In the literature reviewed and summarised in the paper risk assessment has the following common components:

1) Inputs:
    a) Data on the fishery and the fish population (including estimates derived from such data);
    b) A model describing the dynamics of the fishery;
    c) Quantitative descriptions of uncertainty about the data and (or) the model;
    d) Several alternative future management options.
2) Method: Monte Carlo projection.
3) Outputs: One or more performance measures describing the future performance of the fishery under each of the alternative management options.

However, the major problems related to risk assessment are identified as:

1) The lack of a standard approach to present the advice. Two issues are to be decided on this respect: the performance measures to use, and how complex should the presentation be for each performance measure.
2) True versus perceived states: This may involve having a single model and two sets of parameters or two different models. In either case, one model (or parameter set) is taken

as describing the "true" state of the fishery, and the other, how it is perceived by scientists and managers.

3) The value of simple models. Recent works have shown that simpler models can support fishery management better than more realistic ones.

4) The risk of collapse. This is the most negative undesirable event. However, it is difficult to model this event.

There are few examples of risk management in the literature, but the main issues authors want to draw attention to on this respect are:

1) Objective or loss function. This function calculates the performance measure and is to be maximized or minimized accordingly for choosing the best management option.

2) Multiple objectives. When the management objectives are multiple, and possibly conflicting, the objective function has to combine all of them.

3) Eliciting objectives. The authors refer the lack of explicit objectives as the major barrier to effective management.

4.7 Review of Uncertainty Categories

Handling uncertainty is an essential part of a risk assessment and in particular in the risk estimation part of the assessment. The ideal situation is where the total uncertainty can be quantified, but unfortunately this is seldom the case when dealing with human impacts on ecosystems. Although statistical models handle uncertainty, there is yet remaining uncertainty due to model assumptions of various kinds. Sensitivity analysis can resolve parts of this. This section is a review of how a small selection of papers has characterized uncertainty and the role of qualitative uncertainty in risk assessment.

To clarify the uncertainty aspects, uncertainty is often separated into *uncertainty categories*. The literature shows that uncertainty has been divided in several ways. In fisheries science there is a tradition of dividing uncertainties by *their sources*. Francis and Shotton (1997) is an example of this. They divide uncertainty (and based on a review of fisheries science literature) into its following sources: *process, observation, model, estimation, implementation and institutions*. The UKCIP report from 2003 (see Section 4.4) operates with *natural variability, data uncertainty* and *knowledge uncertainty*.

Other parts of the literature divide uncertainties in qualitative characteristics. Wynne (1992) uses 4 types of uncertainties: *risk, uncertainty, ignorance and indeterminacy*. *Risk* is when the system is well known and the probability distribution for different outcomes is known. *Uncertainty* is recognized as when you know the important system parameters, but not the probability distributions. *Ignorance* is uncertainty that is not recognized, and Wynne stresses that ignorance increases with the commitments based on the knowledge that includes uncertainty. *Indeterminacy* is an open-ended kind of uncertainty. For example uncertainty from assumptions in science or assumptions on human behaviour where we cannot evaluate their validity is denoted as indeterminacy. Indeterminacy is a question whether the body of knowledge has been changed to fit the problem or whether the problem has been redefined to fit science.

Funtowicz and Ravetz (1990) divide uncertainty into *inexactness, unreliability* and *ignorance* (or *border of ignorance).* They combine the degree of uncertainty with decision stakes to characterize knowledge production: applied science, professional consultancy and post-normal science. Post-normal science is a concept they have developed that denotes the science needed for policy decisions where decision stakes are high and uncertainty level is high.

Although the papers by Wynne and by Funtowicz and Ravetz are on uncertainty, they are closely linked to risk because both papers are uncertainty in a policy context where stakes are high. While Funtowicz and Ravetz separate uncertainties and stakes, Wynne claims that uncertainty and stake are not independent; indicating that his way of understanding uncertainty is more related to risk. Both Wynne and Funtowicz and Ravetz argue that traditional science (curiosity driven science) is not suitable for the emerging policy problems where stakes are high.

The IPCC workshop (2004) divides uncertainty into 2: uncertainty (quantitative) and confidence (qualitative) and stresses that both are important in assessing the uncertainty.

Klinke and Renn (2006) introduce the concept of *systemic risks*: "Systemic risks are a product of profound and rapid technological, economic and social changes that the modern world experiences every day. They are characterised by high complexity, uncertainty, ambiguity, and ripple effects. Due to these characters systemic risks are overextending established risk management and creating new, unsolved challenges for policy making in risk governance. Their negative effects are often pervasive, primary areas of harm."

They explain the four major properties the following way (quoted):

- *Complexity* refers to the difficulty of identifying and quantifying causal links between a multitude of potential candidates and specific adverse effects. The nature of this difficulty may be traced back to interactive effects among these candidates (synergisms and antagonisms), positive and negative feedback loops, long delay periods between cause and effect, inter-individual variation, intervening variables, and others. It is precisely these complexities that make sophisticated scientific investigations necessary since the dose-effect relationship is neither obvious nor directly observable. Nonlinear response functions may also result from feedback loops that constitute a complex web of intervening variables.
- *Uncertainty* comprises different and distinct components such as statistical variation, measurement errors, ignorance and indeterminacy […], which all have one feature in common: uncertainty reduces the strength of confidence in the estimated cause and effect chain. If complexity cannot be resolved by scientific methods, uncertainty increases. But even simple relationships may be associated with high uncertainty if either the knowledge base is missing or the effect is stochastic by its own nature.
- *Ambiguity* denotes the variability of (legitimate) interpretations based on identical observations or data assessments. Most of the scientific disputes in risk analysis do not refer to differences in methodology, measurements or dose-response functions, but to the question of what all this means for human health and environmental protection. Emission data is hardly disputed. Most experts debate, however, whether an emission of x constitutes a serious threat to the environment or to human health. Ambiguity may come from differences in interpreting factual statements about the world or from differences in applying normative rules to evaluate a state of the world. In both cases, ambiguity exists on the ground of differences in criteria or norms to interpret or judge a given situation. An example for such ambiguity is pesticide residues in food where most analysts agree that the risk to human health is extremely low yet many demand strict regulatory actions. High complexity and uncertainty favour the emergence of ambiguity, but there are also quite a few simple and almost certain risks that can cause controversy and thus ambiguity.
- *Ripple effects* indicate the secondary and tertiary consequences regarding time and space, i.e. functional and territorial dimensions of political, social and economic spheres. The cross-border impact of systemic risks exceeds the scope of domestic regulations and state-driven policies. To handle systemic risks interdisciplinary mechanisms in international governance are required.

The authors argue that a holistic and systemic concept of risks cannot reduce the scope of risk assessment to the two classic components: extent of damage and probability of occurrence. To evaluate risk a list of criteria should be handled: impact categories (probability of occurrence, extent of damage, reversibility, incertitude and others) and the risk classified (they suggest a set of risk classes). The idea is that an assessment of the systemic risks helps the risk managers to understand the uncertainties so that the risk(s) can be classified. Risk management will then depend on the risk class, where a good control of the uncertainties and damage can be based on science while less control demands precautionary and discursive strategies.

4.8 Summary and comparisons

Since the beginning of the 1990s risk is an emerging topic into fisheries management (Francis and Shotton, 1997). The first step for incorporating risk into the decision-making framework in fisheries is to define a common terminology. However, there is a long debate in the literature on establishing appropriate technical concepts.

For example, there are two ways for defining “risk”. The first one is as the probability of something undesirable happening (Hilborn *et al.*, 1993; FAO 1995b; Lane and Stephenson, 1997). Either explicitly or implicitly, this is the usual practice within ICES (see Section 5 for a more detailed description on current ICES standards). The second one refers to the combination of the probability of something undesirable happening and the magnitude of its associated consequences (Rosenberg and Restrepo, 1994; IPCC, 2004; Burgmann, 2004; Willows and Connell, 2003). This definition is more general and is related to decision theory (Berger 1985).

Since FAO (1995b), there seems to be a general agreement on defining uncertainty as “lack of knowledge”. However, as it is discussed in detail in Section 4.7, it is not so clear how uncertainty relates to risk and therefore on the ways uncertainty is classified.

Other terms, like risk assessment, risk analysis or risk management are also usually confounded. The most common approach (Francis and Shotton, 1997; Lane and Stephenson, 1997; Willows and Connell, 2003) is to distinguish two separate processes within the process of dealing with risk: the first one (risk assessment) dealing with the formulation of advice for managers and the other one (risk management) dealing with the ways managers use that advice to make decisions. Risk analysis is then used to refer to the overall process (risk assessment and risk management). However, there are other approaches like the one in Burgmann (2004) in which risk assessment is understood as the "completion of all stages of the risk management cycle, a marriage of risk analysis, adaptive management, decision tools, monitoring and validation" and where “risk analysis is part of the risk management”.

Additional concepts like risk characterization (EPA, 1998), risk identification (Willows and Connell, 2003), risk evaluation (Willows and Connell, 2003), risk estimation (EPA, 1998; Willows and Connell, 2003), risk screening (Willows and Connell, 2003), risk description (EPA 1998), risk ranking (Burgmann, 2004) or risk communication (Burgmann, 2004) are also common in the literature.

When such differences are found on the basic terminology, differences regarding the elements or steps leading up to management decisions could be expected to be even larger. However, and without taking into account the wording, most of the works reviewed identify most of the following steps:

d) Problem identification, stating clearly the management objectives;

e) Translate the management objectives into a conceptual model and define assessment endpoints;

f) Identify hazards and their consequences;

g) Estimate the likelihood and the magnitude of the consequences associated to the hazards (if possible);

h) Communicate the results;

i) Make a decision;

j) Implement, monitor and evaluate the decision.

In many of the cases (Burgmann, 2004; Francis and Shotton, 1997; Lane and Stephenson, 1997) it is emphasized that the process has to be iterative, so that past experience can help to improve the current decision making process. Furthermore, in Willows and Connell (2003) the framework is circular, so that at the end of each of the stages if something is susceptible of being improved is pointed out or new information is available it is recommendable to go back to a previous stage.

In general, a larger effort has been made in environmental management in comparison with fisheries management for defining a common framework. A unique work (Lane and Stephenson, 1997) describes explicitly a framework for decision making in fisheries. In the rest of fisheries applications the framework is only separated into risk assessment and risk management and the emphasis is on the tools that are used for risk assessment and management (Francis, 1992; Rosenberg and Restrepo, 1994; Lane and Stephenson, 1997; Francis and Shotton, 1997). On the contrary, the environmental management framework is described more in depth and the focus is on the underlying conceptual model (EPA 1998, Burgmann, 2004; IPCC, 2004; Willows and Connell, 2003). This allows risk management to be directed not only to choose the option that minimizes the risk, but also the one that addresses specific cause-effect within the conceptual model.

Although several of the reviewed papers and reports address difficulties in quantifying uncertainties and risks, the usual underlying assumption is nevertheless that the uncertainties can be quantified and values can be given quantified weights. There are exceptions though, where the need for communicating non-quantifiable uncertainty is stressed. For example, the IPCC workshop (2004) reflects this in the following recommendations: “An assessment should always include a statement on the confidence of the results, all uncertainties should be clearly stated and rather than presenting the prediction in which the scientists have most confidence, all reasonable predictions should be presented.” We interpret the rationale for this to be that quantified uncertainty is not necessarily a sufficient basis for decision-making. Of the papers, books and reports we have reviewed, Klinke and Renn (2006) have maybe been most explicit on the role of non-quantifiable uncertainty as they argue it should affect the approach taken in risk management. While risk management can essentially be based on science in cases with good control of the uncertainties and the magnitude of possible damage, less control of the uncertainties demands precautionary and discursive strategies, giving science a less dominant role in risk management.

Finally, most of the reviewed works agree on and emphasize the importance of joint work and continuous collaboration and communication between scientists, managers and stakeholders.

5 Current ICES practice of handling risk

In this chapter we will have a closer look at how ICES deals with risk in advice and at how this is developing within the ICES system, all in light of the papers, books and reports reviewed in the previous chapter.

5.1 Context

A number of white papers and international agreements state more or less explicit general objectives concerning the state and uses of the marine ecosystems. These are sustainable use of the resources, the precautionary approach to fisheries management, the ecosystem approach to management etc. The concern for future generations is significant and the regulation of fisheries is a major component in achieving several of these objectives. For some fish stocks, there are agreed harvest control rules, which represent far more specific management objectives like stability of annual catches or stock recovery. In providing advice ICES needs to take both the general and the specific objectives into account.

Most fish stocks are managed separately. Often in fisheries management, the fishing industry contributes with opinions, concerns and advice, but is seldom part of the final decision-making.

Agreements, also state socio-economic objectives, like maintaining settlements in coastal areas, maintain/increase standard of living etc. that ICES does not (have the expertise) to take into account.

Due to time constraint we did not have the opportunity to check whether there are agreements that contain specific objectives related to risk management. It is our feeling though, that they are implicitly embedded in more general objectives.

5.2 Identified harmful events and its consequences

ICES fisheries advice has traditionally focused on one single harmful event; recruitment failure or impaired recruitment. Sustainability is naturally dependent on recruitment, and Blim is chosen as a proxy for impaired recruitment. The definition of Blim is:

The value of B_{lim} is set on the basis of historical data, and chosen such that below it, there is a high risk that recruitment will be impaired (seriously decline) and on average be significantly lower than at higher SSB.

There are two points worth noting regarding this definition. One is the use of the term “risk”. In this case “risk” means “probability” and ICES does not deal with the costs (like loss of yield) of an impaired recruitment. ICES thereby, operates with another meaning of “risk” than in most of the reviewed books, papers and reports in chapter 4. Another point is that it presupposes that rebuilding is possible. Irreversible states of the fish stock or ecosystem are imaginable, but not part of the ICES advice framework.

Fisheries management deals with several requirements for obtaining sufficient spawning stock biomass: regulations on measure size, regulations on landing size, closed seasons and areas and regulating the fishing effort and/or annual landings. To avoid impaired recruitment, also in the longer run, ICES gives advice in accordance with a precautionary framework consisting of reference points for fishing mortality rate and spawning stock biomass.

At the moment, there is a change of focus from avoidance of recruitment failure to target levels in fishing mortality (at least within ICES). The precautionary reference points have in many cases been adopted as target levels by fisheries managers and has, at least by ICES, regarded as unfortunate. The underlying idea of the alternative target level is thus to try to avoid some experienced problems, but also to suggest fishing mortality rates that maximizes yield or at least improves the utilization of a stock. In a risk context the loss of yield can be defined as an undesirable event. However, ICES does not provide much information on the cost of management decisions. Standard ICES advice states whether a stock is overexploited compared to highest yield and presents both graphs and tables on yield per recruit. This gives an indication on loss of yield, but costs in terms of lost yield (or in monetary value) are not handled.

Fishing may cause other events defined as harmful like by-catch of birds and mammals or damage of coral reefs. Advice on stock exploitation and advice on other effects from fishing are treated separately in ICES. At present ICES is developing advice for an ecosystem approach to management, implying that harmful events caused by other sectors than the fisheries sector will be identified and addressed.

ICES do not cover the socio-economic aspects of risk.

5.3 Identifying the uncertainties

For clarifying reasons we separate the following uncertainties in this section:

- The uncertainty in defining the harmful event or defining a proxy for it,
- The uncertainty in assessing or predicting the state and
- The uncertainty from setting/defining the borders of the risk problem.

There is undoubtedly uncertainty associated with the definitions and calculations of Blim as a proxy for impaired recruitment. We will not elaborate this issue, but simply state that this uncertainty is not part of the ICES advice for fisheries management.

The assessment/prediction uncertainty is reflected in the precautionary reference points, Bpa and Fpa. The framework reflects an average uncertainty; meaning that advice does not take into account variations in the uncertainty from year to year. There are a few exceptions of this like the advice on Barents Sea capelin. SGMAS (ICES, 2006) recommends taking into account a list of assessment and prediction uncertainties when evaluating harvest control rules. The report shows that the existing evaluation tools can take various uncertainties into account. The annual stock assessments, on the other hand, are still quite limiting concerning uncertainty aspects.

ICES expresses advice on all stocks rather similarly as if the complexity, uncertainty and risks associated with each stock were the same for each stock. (We are well aware of the exceptions when ICES considers the data basis is too poor for giving standard advice.) Mixed fisheries, stock recovery, interactions with other stocks, environmental impacts and internal stock dynamics affects the complexity and inherent uncertainties associated with the stock of concern and may vary substantially from stock to stock, not only by scale but also more qualitatively. This should be kept in mind when developing a risk strategy. Stock estimation, predictions and quantification of uncertainties may be difficult or impossible. On the other hand, if the objective is to minimize risk it is possible to deal with some uncertainties in an asymmetric manner. For example, if there is reason to believe that the food supply for a certain fish stock is below average, predicted growth can be set at the precautionary side. Ecosystem considerations can also be used in characterizing perceived irreversible risks to supply the information on the probability of an impaired recruitment. (For further suggestions, see chapter 6).

5.4 Interpreting the significance of the results and communication

There is no standard for expressing confidence in results, which ICES advice is based on, but is eventually done. Sensitivity analysis may be carried out, but is not done on a regular basis. However, FLR is an example of tools being developed to enable this. The interpretation of results from simulations when harvest control rules are evaluated seems far more developed (see Study Group on Management Strategies (SGMAS) 2006).

Uncertainties, interpretation ambiguities and risks are poorly communicated in ICES advice.

6 Developing a framework for risk assessment

SGRAMA considers multi-disciplinary participation to be a requirement for success in developing a framework for risk assessment. The Study Group will need expertise from a majority of disciplines within ICES (ACFM, ACE and ACME), but also within social sciences like economy, sociology and especially competence on risk management. We also emphasize that without a close connection with the involved managers, parts of the framework for risk assessment sketched here, will be irrelevant. We thus admit that the outline for a framework presented below necessarily is limited.

Our attempt to start the development of a framework for risk assessment starts with a focus on terminology. Our limited review has shown a multitude of different use of terminology and definitions and the need to clarify and limit the amount of terminology to be used is obvious.

Based on our reviews we recognize that risk assessment frameworks differ in descriptions partly due to differences in context. The similarity of the reviewed frameworks is that they recognize the identification of “risks” as an important part of the risk assessment in addition to risk estimation itself.

The following subsections deal with some aspects of terminology and some aspects around these two of the parts/phases (identification and estimation) that form part of a risk assessment framework. A risk assessment framework will include more steps/phases that in addition to the relationship between risk assessment and risk management frameworks are left for future discussions in the Study Group.

6.1 Terminology

The terminology presented in the following is not an attempt to make a final list of definitions within the field. The description is intended to illustrate the approach taken by the Study Group.

Risk

Risk can be defined as potential harm or expected loss from some present or future process or event. The Study Group choose to use the term risk in a broad manner as consisting of both a likelihood of an event and the severity of the event or the severity of the consequences of the event. The Study Group recognizes that the likelihood or probability of an event may or may not be quantifiable or quantifiable only to certain extent and that severity can be linked to costs in monetary terms or other value terms and will in many situations be demanding or impossible to quantify.

Risk assessment

Risk assessment is the process of, within a certain context, producing estimates of or knowledge of risk(s). The assessment process may be based on previously identified/defined events or adverse effects, but the identification of risk(s) will usually be a part of the risk assessment process. The usefulness of a risk assessment may depend on a “risk assessment policy” being guidelines for value judgement and policy choices, which may need to be, applied at specific stages in the risk assessment process. A risk assessment process should include preparation of and reporting/communicating the results of the assessment

Risk assessment policy

A set of guidelines that facilitates the quantification or qualitative judgement of the severity of the consequences of some event. In situations with incommensurable consequences or when quantification in itself is difficult/impossible, the ranking of consequences could be useful. Such ranking of consequences will include elements of subjectivity.

Risk management

Risk management includes:

- The process of creating a risk assessment policy through evaluation of the severity of the adverse effects. This process is fundamental for the risk assessment itself and will involve scientists, managers and stakeholders. Whether this should form a part of a risk assessment framework or not is an open question, but the activity is a part of the interface between scientists, managers and stakeholders and is essential in building a common understanding of the risks in question.
- Based on a risk assessment select and decide on regulatory measures and control options.
- And to implement, monitor and control these.

6.2 Identifying risk

An important element in a risk assessment process (within a fisheries advice context) is related to the identification and formulation of the underlying problems themselves, basically answering the question: What is it we want to avoid? This must in many cases be seen in relation to: What is it we want to achieve? The issues will range from ecosystem aspects to socio-economic. Two examples of simplified definitions of risk are "potential harm" and "expected loss". Both "definitions" imply some knowledge of likelihood and the severity of the consequences or impact of some kind of event or undesirable state. The quality (and usefulness) of any risk assessment will depend on how well one is able to identify the various events or damages in question. A risk assessment that is not able to identify and deal with serious threats may not produce the information needed for good management decisions. Mapping of potentially contradictory objectives related to risk would be one part of risk identification.

The ICES community is well known with the concept of B_{lim} and SSB falling below B_{lim} is considered to be harmful because B_{lim} can be a proxy for the event of reduced recruitment due to overfishing. B_{lim} is not defined for a range of stocks. And for some stocks where a level of SSB where recruitment is impaired cannot be defined B_{loss} has been chosen as B_{lim}. Then the potential harmful event of falling below B_{loss} corresponds to the rather vague potentially harmful event of entering a situation where the dynamics of the stock is unknown. Loss in yield can be caused by growth overfishing and can hardly be called an event, but rather more the non-beneficial consequence of a process/practice.

Potentially harm may occur not only as caused by human activity, but also due to natural phenomena. The ability to limit the risk will in such cases mostly be linked with the ability to handle the consequences of such events under a continuously changing environment.

6.2.1 Identifying harmful or negative events

The Study Group considers that some indication of the activity needed within risk identification as part of a risk assessment includes:

- Risk identification would benefit from multidisciplinary participation
- The context in which risk is to be identified needs to be clarified (especially in a multidisciplinary setting).
- The identification itself is answering the following two questions: What can happen? How can it happen? Several authors including Burgmann (2005) mention checklists, unstructured and structured brainstorming as methods to assemble list of events.
- After the identification: Are the consequences properly identified and is the severity or loss clear from the risk management policy?

- Risks can be grouped or handled by the cause of the risk or more in line with grouping the consequences. Forming a matrix of both could be useful (Table 4.4.3.1 in WGECO 2006 is one candidate for a template) in establishing causal links.

6.2.2 Causality

The linking of cause and effect is an important step of the risk identification process. Establishing causality will help creating decision criteria for risk management (prevent or repair) and is required if traditional quantification of risk shall be calculated.

6.2.3 Conceptual models

Influence diagrams (flow charts with linkages) or conceptual models are useful tools for systematic handling of causality, but also for communication of the problems in question. It is also a good method of summarising the findings in the identification of risks.

6.3 Risk estimation

6.3.1 Expressing "harms" as measures

Blim is a translation of recruitment failure and is thus only a proxy for an unwanted event. "Harms" like unemployment and destruction of coral reefs need to be expressed in terms of quantified limits or in qualitative terms. If quantified, possible uncertainties should be expressed.

6.3.2 Translating human impact and activity

Also human impact in relation to the unwanted event may need to be represented by measures. Estimates of spawning stock biomass and fishing mortality rate or days at sea are some examples of quantified measures. No fishing with bottom trawl in a certain area is a qualitative management measure.

6.3.3 Likelihood/probability

Section 4.7 of this report is a review of some ways to treat or classify uncertainty. An important part of the process will be to distinguish when one is able to quantify the likelihood or probability of some event and when one must use a more qualitative approach.

The quantification of likelihood or probability will usually rely on a set of (model) assumptions and these should be stated clearly. There is a long range of problems associated with the estimation of very low probabilities and a typical challenge is how to estimate the probability of some event that has not been observed previously (or not within the range of the available empirical data). Situations will arise when the likelihood cannot be quantified and other approaches should be considered. Risk ranking methods uses qualitative estimates of likelihoods and consequences. Such methods have some pitfalls and being subjective is one. Risk ranking methods need some preparation and planning, apart from the participation of expert groups.

In between situations of quantifiable and non-quantifiable likelihoods one can find the concept of relative likelihood useful if one has some information of the dynamics involved. (What does it take to double the likelihood? Or halve it?).

6.3.4 Consequences/severity/loss

Assessing the severity of the consequence or levels of consequence is needed as a part of assessing a stock. How the consequences are valued is critical if several risks are to be compared. How is some loss to the ecosystem to be compared with a calculated monetary loss related to loss of fishing opportunities?

The scientific community should be very careful with participation in the process of relating a value to consequences. However, science may help in clarifying what consequences different risk management strategies have. The process of creating and updating a "risk assessment policy" should involve both managers and stakeholders. Steps must be taken to ensure scientific integrity. Good communication is essential for learning and improving.

6.3.5 Validation

All results that form a basis for risk management advice should be validated. If the results are quantities, a sensitivity analysis is a useful method. All quantification of likelihood is based on some assumptions and sensitivity to these should be explored. Examples of such assumptions are the choice of statistical distributions to parameterise the probabilities and choice of models itself. The sensitivity analysis is the step beyond the estimation of the variance of a probability estimate. A sensitivity analysis is not always possible, like when the number of model parameters is too high or when an assessment is more quantitative. Then an expressed trust in the results should be stated.

6.4 Risk communication

Risk identification and risk assessment forms parts of a risk assessment. Risk communication is another vital part of a risk assessment framework. This is the communication of the results of the assessment and differs from the communication needed in establishing the risk assessment policy. This important topic must be addressed in future meeting of the Study Group.

6.5 Future work for the Study Group

The following paragraphs describe some of the work that should be planned for future meetings.

- Continue the literature review. (An obvious candidate can be found in for the review process is Standards Australia (2004a; 2004b) together with examples of how this framework has been applied within fisheries systems. Other relevant examples/approaches will also be reviewed.)
- Continue developing terminology and concept definition list.
- Describe the main phases within the risk assessment framework.
- Study the relationship/interaction between and within the different phases within the risk assessment framework.
- Study the relationship between the risk assessment and risk management frameworks.
- Revise current available methods and tools for the different phases within risk assessment. If necessary develop them or set the basis for future development.
- The Study Group will at some stage produce specific examples of risk assessment in fisheries.
- Dedicate future meetings to specific aspects relevant for risk assessment such as sociology, economics, political decision making, and discussing those with invited field experts/managers/stakeholders to optimise the communication process and to complete the list of, for instance, potential hazards, risks, consequences, etc. This will improve the process of finding quantifiable proxies in an early stage of a risk assessment and reduce the need for later major revisions.
- Finding better ways that help to understand what "severity" really means and how the causal pathways and the (magnitude of) effects can be appropriately

quantified; for instance, we must be able to answer the questions: What does a loss in SSB as a proxy for severity do actually mean for the stock: collapse, extinction, impaired recruitment? Are there competing loss definitions/criteria such as the reduction of fishermen's future income, the degradation of the ecosystem, etc.?

7 Working documents

Two working documents were presented to the Study Group. Both are listed below and can be found in Annex 4.

WD1: Joachim Paul Gröger and Rodney Alan Rountree: A rebuilding framework for an optimal control of multispecies, multistock, and/or multiarea fisheries.

WD2: Coby Needle, FRS Marine Laboratory, Aberdeen: Management advice accounting for model uncertainty

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Annex 1: List of participants

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Annex 2: SGRAMA terms of reference 2006

The **Study Group on Risk Assessment and Management Advice** [SGRAMA] (Chair: Knut Korsbrekke, Norway) will be established and meet at ICES Headquarters from 18–21 April 2006 to:

a) to review and report on available methodologies for risk assessment and frameworks for risk management within and outside the fisheries sector;

b) on the basis of the review, start development of a framework and operational guidelines, for risk assessment and advice which includes considerations on risk management. Risk assessments should *inter alia* relate to conservation limits and targets for exploitation of fish stocks taking into consideration the ecosystem effects of fisheries and environmental variability and management considerations should relate both to the production of such assessments and institutional aspects of risk management decisions and implementation. The framework should link to the framework for management strategies developed by SGMAS with the scope of ultimately being integrated with these;

c) consider and report on training needs and possible modalities for training to disseminate knowledge about risk assessments to members of ICES expert groups;

d) outline the kind of relevant information that will be required for risk assessments.

SGRAMA will report by 5 May 2006 for the attention of the Resource Management, the Living Resources Committee as well as ACFM, ACE, ACME.

Supporting Information

PRIORITY:	The work is essential for ICES to progress in the development of its capacity to provide advice on fisheries and marine management which includes considerations of risk. Such evaluations are necessary to fulfill the requirements stipulated in the MoUs between ICES and Commissions
SCIENTIFIC JUSTIFICATION AND RELATION TO ACTION PLAN:	[Action numbers 3.2, 3.4, 3.5, 3.12, 4.2, 4.3, 4.5, 4.11.2, 4.13, 4.15, 7.2] The SGRAMA report is a first step in establishing guidelines for production of risk assessments and inclusion of considerations of risk management in the advice. Risk assessment and risk management is an important filed in several branches of science. The SGRAMA aims at drawing on the experience from other branches of science, and to include that experience in the development of risk assessment and risk management in fisheries science. The field covered by the SGRAMA is close to the fields of the SGMAS and WGFS. However, the scope of the SGRAMA is to focus on risk issues while that of SGMAS is in developing operational guide-lines to enable ICES to respond to managers' request for advice on development and evaluation of management strategies even at present, while the scope of WGFS is mostly on improving the understanding of how fisheries systems work. Clearly, the SGRAMA should draw on the insight provided by the SGMAS and WGFS. The outcomes of SGRAMA will eventually be incorporated in the guidelines for evaluation of management strategies under development by SGMAS.
RESOURCE REQUIREMENTS:	
PARTICIPANTS:	Experts with qualifications regarding assessment and institutional aspects of risk assessment and management. Effort should be made to attract participants with experience in risk assessment and management outside the fisheries sector.

Annex 3: Recommendations

The Study Group addresses the following recommendation to the chairs of RMC, LRC, ACE, ACFM, ACME, WGECO, FSWG, SGMAS and the ICES General Secretary:

The participation in the Study Group was far below what is required to address the issues described in the ToR's. The Study Group is in need of multidisciplinary participation both from within and outside the ICES. Expertise within social sciences like economy, sociology and especially competence on risk management will be crucial. The Study Group would benefit from participants with expertise especially in ecology and ecosystem effects of fishing and management advice but also within environmental monitoring and the effect of contaminants. Interaction with related working groups (like WGECO, FSWG and SGMAS) and EU projects (like PRONE) would also be beneficial for SGRAMA.

WKREP (2006) pointed out in their summary: "in order to achieve improved commitment to the Expert Group and Committee work excellent contents and attractiveness is needed."

Participation in the Study Group should be encouraged.

The following recommendation is addressed to ICES in general:

The Study Group recommends that the use of the term "risk" is handled more carefully. Risk should mean something more than the probability of some (potentially) harmful event and we recommend that at least the definition used and context is specified.

Annex 4: Working documents

WD1: Joachim Paul Gröger and Rodney Alan Rountree: A rebuilding framework for an optimal control of multispecies, multistock, and/or multiarea fisheries.

WD2: Coby Needle, FRS Marine Laboratory, Aberdeen: Management advice accounting for model uncertainty.

A rebuilding framework for an optimal control of multispecies, multistock, and/or multiarea fisheries

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Abstract
We outline the fundamentals of a simple but very flexible stock rebuilding framework model that is based on a nonlinear optimization algorithm with all constraints set up explicitly with clear optimality for controlling fishing effort (or fishing mortality) and maximizing landings (or economic value). The underlying theory originated from economic/econometric control theory and was developed to aid in small and large business management and for government management and economics. As applied to fisheries, our approach is intended to be a tool for finding an optimal medium to long-term management strategy. We present a formulation of the basic theory together with selected model feature variations such as inclusion of biological interactions and optimization based on economic yield rather than physical yield. For illustration purposes we present an application of our optimization model to a simplified quasi-realistic multispecies fisheries management example based on an important North American groundfish fishery located on Georges Bank (GB) and the adjacent Gulf of Maine (GOM) within the western North Atlantic. The species and stocks chosen include the haddock, *Melanogrammus aeglefinus* (stock), yellowtail, *Pleuronectes ferrugineus* (GB stock), witch flounder, *Glyptocephalus cynoglossus* (GOM and GB combined stock), American plaice, *Hippoglossoides platessoides* (GOM and GB combined stock), and Atlantic cod, *Gadus morhua* (separate GOM and GB stocks). The simplified application illustrates how to alternate options and conditions to determine the best modeling strategy. We consider our stock rebuilding approach as an adaptive dynamic framework that is modular in construction and amenable to further improvement as our knowledge increases.

Keywords: fishery control, fishery management optimization, technical species interactions

Introduction

The key objective in fishery management is to maximize landings (or economic value) on a sustainable level. However, sustainability can be interpreted in different ways which can be subject to different constraints. Therefore managers have developed different mechanisms to maintain fisheries based on either effort or quota controls, such as fishing capacity, gear, area or catch restrictions . Traditional management strategies are often applied in equilibrium settings and relate to maximizing production, often based on a catch-and-effort curve. These techniques have been developed in a single-species environment (see however MSVPA) even though many fisheries take many species simultaneously. But even in a single species setting, the conventional techniques leave much to be desired as these techniques do not always yield a clearly defined maximum. In addition, the theories that underlie these techniques are brought into question as they usually approach the goals purely analytically and without clear definition of constraints, in that most of their assumptions are implicit, and because they often achieve a poor fit to highly variable large fishery data sets.

At present, fishery management strategies are usually performed in four major steps as outlined in Figures 1 and 2:

(Step 1) collecting population relevant data (commercial, market sampling and research survey data)

(Step 2) estimating the relevant population parameters (stock abundances, fishing mortalities, etc.)

(Step 3) predicting the future and simulating scenarios based on different management options and on the results of step 2 (catch-effort or biomass-effort relationships) (see Fig. 2)

(Step 4) under the given circumstances, taking the most plausible result(s) of step 3 as optimal management strategy.

Currently, the commercial catch information used in Steps 1 and 2 is calibrated by survey information as these surveys are to some extent standardized and normalized (Fig. 1). The estimated parameters are usually stock sizes in numbers and fishing mortalities by age, but depending on the type of model used other parameters such as catchabilities can sometimes be estimated (Fig. 2). This approach suffers from problems such as data inconsistency, a relatively limited temporal and spatial resolution, and the fact that environmental and multispecies interactions are not considered. In addition, another major problem seems to be the difficulty of transitioning from the retrospectively estimated parameters to a future oriented medium to long-term management strategy and its implementation. However, the transition can potentially be accomplished by using the power of a retrospectively oriented prediction model to forecast the future, or by using some tool for generating scenarios (Fig. 1). Traditionally, these scenarios are generated using various analytical MSY (Maximum Sustainable Yield) approaches in which most of the assumptions are implicit, and typically are based on some type of catch-and-effort curve (Fig. 2).

In this paper we introduce a numerical procedure using a non-linear optimization algorithm which we adopted from econometric control theory, as first suggested to us by Azadivar, Truong and Rothschild (School for Marine Science and Technology, University of Massachusetts at Dartmouth, personal communication), that can serve as a bridge between parameter estimation and scenario testing and forecasting (i.e., between Step 2 and 3 of the management procedures outlined above). The idea of using aspects of dynamic programming in fisheries was first introduced by Rothschild (1972) in his treatise on defining fishery effort. Studies that more explicitly addressed the issue of maximizing (optimizing) a single-species harvest control rule soon followed (Walters 1975, Hilborn 1976). Since these early studies, other researchers have discussed harvest control rules and how to optimize them in a single-species setting, including a recent study by Quinn and Deriso (1999) who discuss detailed features of various types of objective functions.

We further advance these studies by describing how to set up an open framework and optimize a multispecies harvest control rule that is subject to biological constraints. The approach is fairly explicit and open and is intended to be a framework for rebuilding fish stocks optimally in the medium to long-term time horizon. Hence, unlike most other models our approach does not "passively" predict the future stock development based on past values but "actively" seeks to optimally control it. We feel that, because of its framework nature, our model is capable of more easily incorporating other types of data, such as multispecies and environmental interactions and economic considerations, than traditional fisheries models. After first describing the model framework and variations to allow incorporation of technical and biological interactions, we then illustrate how our model can be implemented by applying it to a quasi-realistic example based on an important North American fishery located on Georges Bank within the western North Atlantic.

Methods

The theoretical framework

The idea and basic outline of the rebuilding model is diagramed in Figures 3 and 4. We start with a given planning horizon, in this case of 10 years encompassing the period 2005-2014. The period starts with an initial multi-area, multi-species and age-disaggregated biomass in 2004 (i.e. biomass resolved by area, species, age class) and ends with the target biomass in 2014. Although in principle the rebuilding period can be less than the planning horizon and may be variable among species, for simplicity in this paper we define them as equivalent and the same for all species. The initial biomass is the last retrospective year's biomass that was "estimated" by any traditional modeling procedure used, for example such as ADAPT (see Gavaris 1990), statistical catch-at-age models (Deriso & Quinn 1999), or the Kalman filter (see, for instance, Harvey 1989). The target biomass is the rebuilding biomass to be met at the end of the rebuilding period that is set by the fishery managers. For example, one might choose to use the target biomass derived from the precautionary approach (B_{PA}).

Starting with these initial conditions, we then track the annual biomass development subject to fishing activities during the rebuilding period (planning horizon). As we allow some fishing activity (for instance, in terms of either days-at-sea or fishing mortality) we will get back some annual yield (split up by area, species, and age class of concern) (Fig. 4). As the idea is to control the fishing activity, we must constrain this by boundaries using an upper limit for the fishing effort or the fishing mortality (for instance, using F_{MSY} as an upper value for it). The need for constraints can arise due to biological limitations resulting, for instance, from bycatch, recruitment, rebuilding issues, etc..

Under this framework the optimal solution in terms of annual effort allocation (by management unit expressed as species, area, stock, or may be as fleet, segment, metiér, etc.) will be determined by maximizing the total yield subject to these constraints (i.e. within these effort boundaries). The framework must be set by fishery managers through the definition of limiting fishing effort (or fishing mortality values) and rebuilding targets. In other words, the objective is to find the optimal constellation of fishing effort f (or fishing mortality F) values by area, species or stock, age, and year (or by any other managment unit such as fleet, metiér, segment, etc.) which maximizes the total yield (in physical or economical units) at the end of the planning horizon (or rebuilding period) without depleting the (spawning) stock biomass by not allowing the stock size to go below a pre-set target biomass.

Hence, the control or instrument variable is the fishing effort f (or the fishing mortality F), the objective function is the total yield in physical or monetary units being subject to maximization, the constraints are, for instance, that:

"one ton of haddock will have X tons cod as bycatch so that the catch of cod must be limited to 50 kg per trip" and/or

"by 2014 the SSB of cod must be equal or larger than the set rebuilding SSB target" and/or

"by 2007 the SSB of haddock must be equal or larger than the set rebuilding SSB target" and/or

"the fluctuation of the annual total catch should be minimal to ensure a relatively stable income for the fishermen".

Closed areas or seasons can simply be implemented as effort constraints by setting days-at-sea to 0 (DAS = 0) either constantly or periodically in the area of concern. Thus, the principle idea is to simulate scenarios and iterate model parameters as long as these are non-optimal in terms of an optimization criterion.

Our rebuilding framework can be implemented numerically using algorithms based on methods of nonlinear optimization. Thus either maximization or minimization algorithms can be used to optimize the objective function (however, in the case of minimization algorithms the sign of the optimization criterion must be reversed as the goal is maximization of the function). Fortunately, a large set of different algorithms with different requirements can be found in the literature on numerical mathematics, and many of these have been implemented in various programs such as MATLAB (see http://www.mathworks.com/) and SAS (Statistical Analysis Software; see http://www.sas.com/; SAS Institute Inc. 1999). Anyhow, during the search process, an iterative process is used to return the objective function's value for each iterated alternative. This iterative approach is sometimes called simulation, so that the entire algorithm can also be called simulation based optimization (Azadivar 1992). It is usually necessary to initialize the algorithms with starting F (or f) values. Some of the nonlinear optimization algorithms (e.g. the Nelder-Mead or the Dual-Quasi-Newton Optimization Algorithms) function without the need of specifying derivatives (e.g. without implementing a Hessian or Jacobian matrix). We use SAS version 9.1.3 , specifically the integrated matrix language SAS/IML (SAS Institute Inc. 1999), for solving the equations because of its ability to manipulate large-scale matrices while at the same time allowing the simulation to be embedded into a macro-based statistical environment, making it possible to vary options and carry out sophisticated statistics.

Model features

In the following sections we provide a detailed description of several model features including, the computation and maximization of the physical and economic yields, stock size computation and incorporation of recruitment, incorporation of biological and technical interactions, and conversion between fishing effort and mortality. In each model feature case, we consider one species in one specific area that leads to the set of equations below. Note, although all subsequently stated model equations could be easily extended and implemented using age, year, area, and species disaggregated values and thus subscripts, for convenience and legibility we suppress the subscripts for area and species in most cases presented herein except where necessary. The linkages between these model features and the equations that describe them are illustrated in Figure 4, providing an overview of the underlying numerical structure upon which the control theoretical algorithm is built.

On the computation of physical yield and its maximization

The central equation for calculating the annual (physical) yield per area and species is given by Baranov's catch equation (Baranov 1918)

$$C_{a,y} = \frac{F^*_{a,y}}{Z^*_{a,y}} \times N_{a,y} \times (1 - e^{-Z^*_{a,y}})$$

with

$C_{a,y}$: *catch in numbers fish per age class and year*

$Z^*_{a,y} = F^*_{a,y} + M_a$ **(1)**

$F^*_{a,y} = \hat{F}_{a,y} \times S_a$

(*i.e.* $F^*_{a,y}$ *takes into account the age-specific selectivity pattern* S_a)

$\hat{F}_{a,y}$: *during the maximization process estimated fishing mortality*

a : *age*

y : *year*

S_a can either be an element of a matrix of empirical selectivity values or might be specified by some selectivity function. To make the approach more flexible, it would be valuable to add a further control via mesh sizes using some selectivity function of the form

$$S_{length} = \frac{1}{1 + e^{\hat{s}_1 - \hat{s}_2 \times length}}$$

with **(2)**

$\hat{s}_1, \hat{s}_2$: *prior estimated parameters from net selection experiments*

Modifying this function in accordance with Bethke (2004) allows one to convert the mesh size as a regulation measure into selectivity values and thus explicitly affects the resulting product between fishing mortality and selectivity. In this case the selectivity function is based on a logistic regression approach whose model parameters must be estimated from prior experiments. The resulting S_{length} values need to be further converted into age based ones.

Multiplying the catch in numbers by a body weight vector W with age-specific elements W_a gives the yield in biomass (kg):

$$Yield_{a,y} = C_{a,y} \times W_a$$

with **(3)**

W_a : *weight matrix*

The weight vector W may either contain empirically derived mean weight values W_a by age and species or values W_a specified by some empirical weight function.

Totaling this up gives the total annual yield that also forms the major component of the objective function (optimization criterion) to be maximized:

$$Total\ Yield = \sum_a \sum_y Yield_{a,y} \tag{4}$$

Since we have to make sure that the total biomass at the end of the rebuilding period matches the target biomass, some penalty function (per species) must be incorporated (if the rebuilding period varies for different species then the summation takes place over different time horizons)

$$Penalty\ term_{species} = \max\left(0,\ B^{(target)}_{species} - B^{(total)}_{species}\right)$$

$$\underline{with}$$

$$B^{(target)}_{species} : target\ (rebuilding)\ biomass\ per\ species$$

$$B^{(total)}_{species} : total\ biomass\ per\ species\ at\ the\ end\ of\ the\ rebuilding\ period \tag{5}$$

I.e. we penalize differences larger than 0 and ignore negative differences. This can be considered as a further kind of constraint (multiple constraints besides constraining the f or F values). The penalty term can be extended by multiplying it with a species-specific coefficient $\theta_{species}$ in order to weight some species over others. Setting the elements of the penalty coefficients' matrix to 1 gives every species the same weight. The objective function then becomes

$$Objective\ function = Total\ Yield + \left(\sum_{species} - \left(\theta_{species} \times Penalty\ term_{species}\right)\right) \tag{6}$$

This functions means that the total yield will be maximized while at the same time the values of the species related penalty terms are minimized (i.e. the sum of negative differences will be minimized as we maximize negative values).

In order to stabilize the expected yearly catches (keeping the catch stable over time is more attractive for fishermen as it keeps their income constant in time) the objective function can be further extended by introducing a smoothing term

$$Smoothing\ term_{species} = \sum_{y=1}^{end\ of\ rebuilding\ period_{species}} \left(Yield_{y,\ species} - Yield^{(desired)}_{species}\right)^2$$

$$\underline{with}$$

$$Yield^{(desired)}_{species} : a\text{-}priori\ set\ desired\ level\ of\ yield\ per\ species$$

$$Yield_{y,\ species} : annual\ yield\ per\ species\ (aggregated\ over\ age) \tag{7}$$

In contrast to the penalty term described above here we penalize squared differences, that is both positive and negative differences as we want to reduce the fluctuation in general. The smoothing term can be considered one component of multiple constraints. As part of the objective function it will be subtracted from the given total yield and thus becomes minimized.

Again this function can be extended by multiplying it with a species-specific weighting coefficient $\lambda_{species}$ in order to give some species priority over others. The modified objective function to be maximized then becomes

$$\begin{aligned} Objective\ function &= Total\ Yield \\ &+ \left(\sum_{species} -(\theta_{species} \times Penalty\ term_{species}) \right) \\ &+ \left(\sum_{species} -(\lambda_{species} \times Smoothing\ term_{species}) \right) \end{aligned} \quad \mathbf{(8)}$$

This functions means that the total yield will be maximized while at the same time the summed negative terms will be minimized (maximization of a negative value). Rather than using an arbitrary $Yield_{y,\,species}^{(desired)}$ in Eq. (7) an annual average yield may be used although this would increase the computer runtime somewhat as the average value will change during each iteration. We should keep in mind that components of Eq. (8) may be area-specific and thus may be added up over area to give the overall objective function. It can be further inferred that not only the rebuilding target but also the rebuilding period might be different for different species. In such a case the summation in Eq. (4) (2nd sigma sign) but also in Eq. (7) takes place over a different number of years for different species.

On the computation of economic yield and its maximization

An alternative objective function (optimization criterion) based on economical rather than physical yield can alternatively be derived following a similar procedure. Multiplying the physical yield in biomass (kg) with the species-specific unit price and totaling this up gives the total annual economical yield that then forms the major component of a modified objective function:

$$\begin{aligned} &Total\ Yield = \sum_{a} \sum_{y} Yield_{a,y} \times P_y \\ &\underline{with} \\ &P_y : unit\ price\ (price\ per\ kg) \end{aligned} \quad \mathbf{(9)}$$

Here the unit price may differ by species but usually not by area (i.e. it can be considered constant, for instance, for different areas on Georges Bank). Depending on the species and on whether the fish is used for consumption or not the unit price may also vary by other factors such as quality categories or size groups. Furthermore, the unit price may change with the amount of fish landed (economical rule of supply and demand). This may require the use of a feed back price function instead of a simple price function (interdependent or simultaneous price model) for calculating the unit price dependent on the amount of fish landed. As for the physical yield we can add penalty and smoothing terms to the economic yield. If information on costs is available the objective function might be modified by maximizing the profit as a criterion instead of the income:

$$Profit = Total\ Yield - Total\ Costs \quad \mathbf{(10)}$$

Also here, we should keep in mind that Eq. (9) contains species- and area-specific elements and thus must be further added up over species and area to give the overall objective function.

On the computation of stock sizes and incorporation of recruitment

Eq. (1) contains elements $N_{a,y}$ of a stock size matrix N. Except from $N_{1,y}$ age-specific stock sizes will be modeled as

$$N_{a,y} = N_{a-1,y-1} \times (1 - e^{-Z^*_{a,y}}) \ ; \quad for\ 1 < a < age_{\max}$$

with

$$\begin{aligned} Z^*_{a,y} &= F^*_{a,y} + M_{a,y} \\ F^*_{a,y} &= F_{a,y} \times S_a \\ &\quad (i.e.\ F^*_{a,y}\ takes\ into\ account\ the\ selectivity\ pattern\ S_a) \\ a &: age \\ y &: year \end{aligned} \tag{11}$$

$N_{1,y}$ will be specifically calculated as recruitment of the preceding year either using a density depending or independent stock-recruitment function; in the case of density dependence we use the Ricker approach for estimating $N_{1,y}$ (Ricker 1954), i.e.

$$N_{1,y} = R_{y-1}$$

with

$$R_y = R_1 \times SSB_y \times e^{-R_2 \times SSB_y} \tag{12}$$

SSB_y : *annual spawning stock biomass (index)*
R_y : *annual number of recruits (index)*
R_1, R_2 : *function parameters to be estimated*

In the case of a weaker density dependence we will use the Beverton-Holt approach for estimating $N_{1,y}$ (Beverton-Holt 1957), i.e.

$$N_{1,y} = R_{y-1}$$

with

$$R_y = \frac{SSB_y}{SSB_y + g \times R_{\max}} \times R_{\max} \tag{13}$$

SSB_y : *annual spawning stock biomass (index)*
R_y : *annual number of recruits (index)*
$R_{\max}$: *asymptote of the recruitment curve*
g : *slope*

In both cases simple linearizations exist. If recruitment shows some dependence on environmental factors we will use an extended recruitment function (see Hilborn & Walters, 1992); for example, using a linearized version of the Ricker S/R relationship the effect can be incorporated as a linear combination turning the simple regression model into a multiple regression one:

$$\ln(\frac{R_y}{SSB_y}) = \ln(R_1) - R_2 \times SSB_y + c \times E_y$$

$$or \qquad \textbf{(14)}$$

$$\ln(\frac{R_y}{SSB_y}) = \ln(R_1) - R_2 \times SSB_y + c \times (E_y - \bar{E})$$

E_y is some environmental factor such as temperature, c is some regression coefficient, R_1 and R_2 have the same meaning as in the Ricker curve above. The second part expresses the environmental factor E_y relative to its average which in some cases may be easier to interpret.

The recruitment functions given above can be easily replaced by other types of recruitment functions such as segmented regression approaches or simply by conditional vectors of discrete empirical values.

On the computation of biomass and spawning stock biomass

The spawning stock biomass $SSB_{a,y}$ will be calculated taking into account the age-specific maturity and weight pattern

$$SSB_{a,y} = N_{a,y} \times W_a \times Mat_a \qquad \textbf{(15)}$$

which, if summed up over age, is giving the total annual spawning stock SSB_y. Consequently, the biomass $B_{a,y}$ is derived by

$$B_{a,y} = N_{a,y} \times W_a \qquad \textbf{(16)}$$

which, if summed up over age, gives the total annual biomass B_y.

On the incorporation of technical and biological interactions

Species interactions can be addressed in different ways, dependent on whether we consider technical (e.g. bycatch issues) or biological interactions (e.g. predator-prey interactions). One way to incorporate technical interactions is by using a simple bycatch matrix containing values of observed proportions (ratios per target species) of caught species sorted by target species in the fishery. If we at the same time take into account the age-specific selection pattern, this then leads to the following re-formulation of the fishing mortality problem

$$F^*_{a,y} = \hat{F}_{a,y} \times S_a \times BC_a$$

and

$$Z^*_{a,y} = F^*_{a,y} + M_a$$

with **(17)**

BC_a : *age-specific bycatch*
$\hat{F}_{a,y}$: *during the maximization process estimated fishing mortality*
S_a : *age-specific selectivity pattern*
a : *age*
y : *year*

Similarly, the multispecies interactions on recruitment level can be incorporated in a number of different ways, for example, by using a linearized version of the Ricker S/R relationship for haddock in which 2-year old predator feeds on prey recruits (see Hilborn and Walters, 1992)

$$\ln\left(\frac{R_{y,\,prey}}{SSB_{y,\,prey}}\right) = \ln(R_1) - R_2 \times SSB_{y,\,prey} + c \times (predator\ density)_{a=2} \qquad \textbf{(18)}$$

Also incorporating predator-prey relationships on a population level in a later stage is in principle not difficult; for example, this can be done by splitting up the natural mortality into two components such as

$$M_a = M_{a,\,predator\ species} + M_{a,\,residual}$$

with **(19)**

$M_{a,\,predator\ species}$: *natural mortality caused by predation through a predator species*
$M_{residual}$: *natural mortality caused by other reasons*

The real difficulty arises from the question of how to estimate the natural mortality components in terms of model parameters. In order to do so, one could consider correlations in species' occurrency or as in case of the traditional MSVPA consider stomach contents, consumption rates, etc..

On the conversion of fishing effort into fishing mortality

The conversion of fishing effort f (for instance, days-at-sea) into fishing mortality F is another important issue to be considered. The reason for this is, that in contrast to fishing effort f (for instance, in terms of days-at-sea), which is the actual variable to be controlled and thus used by fishery managers, the fishing mortality F is the decision variable, i.e. the parameter to be numerically optimized in the model. We thus have to take into account the catchability q which is the interfacing coefficient between both quantities, i.e.

$$F = q \times f \qquad \textbf{(20)}$$

The catchability includes both biological and technological effects that are sometimes formally decomposed into the two separate components

$$q = q^{(availability)} \times q^{(efficiency)} \tag{21}$$

where the first component represents the availability of fish in the swept area of the bottom trawl, and the second a quantity which measures the gear efficiency. The availability is assumed to be biologically triggered, e.g. species, size (age), area and time dependent; whereas the efficiency is assumed to be ship, gear, species, size (age), and area (for bottom trawls) dependent. In most cases it is practically difficult or even unrealistic to determine q, never mind to decompose it in it's components. That is why researchers often consider both coefficients $q^{(availability)}$ and $q^{(efficiency)}$ as constants and set them to 1. However, the catchability could be derived from area- and time-disaggregated industry-based surveys that may be compared and calibrated with standardized NMFS (National Marine Fisheries Service) surveys. The basic idea would be to estimate the ratio (see for instance, Harley and Myers 2001, Walsh 1996)

$$\hat{q}_{species,area,y} = \frac{CPUE^{(industry)}_{species,area,y}}{CP\hat{U}E^{(survey)}_{species,area,y}} \tag{22}$$

where the expected density values may be derived from scientific survey CPUE data using a krigging method (Stein 1999); these data may be taken, for instance, from NMFS. In the case that these data are not age-based, information from selectivity experiments could be used and the estimated catchability coefficient multiplied with the derived selectivity pattern to get an age disaggregated catchability, i.e.

$$\hat{q}^{*}_{species,area,a,y} = \hat{q}_{species,area,y} \times S_a \tag{23}$$

The uncertainties may be investigated based on bootstrapping procedures using stochastic rather than deterministic functions.

Implementing stochasticity, bias, and ideas of risk assessment

Input values such as inital abundance values, weights, maturity observations, recruitment, etc. are prone to errors. These errors can be of systematic (bias) or of random nature (stochasticity) and address, for instance, the fact that initial abundance values might have been overestimated, for instance, by 20% or that recruitment varies randomly with some variance around the deterministic/estimated function chosen. Systematic bias can be easily implemented merely by multiplying the relevant quantities with some weight factor, for instance, 0.8 to address the fact that this quantity's input is only 80% in size and not 100%. Depending on the type of recruitment function randomness can be either added as an additive or multiplicative term using an appropriate distribution function, i.e. random number generator, and correct seed (start) values. Here, the seeds should be chosen in a way that the generated streams of random numbers will be annually independent of each other.

The so called implementation error, which is an error addressing the fact that the fishermen may spend more effort or catch more fish than stipulated, can be incorporated by not using the optimal F values generated by the optimization procedure but higher F values for calculating the future stock dynamics; as an example, suppose we have an annual 20% implementation error, then we multiply the optimal F values with 1.2 and use those for the calculation of next year's stock dynamic. Letting run the procedure, say, 1000 times will give 1000 different results. Thus, all these error sources together translate the previously purely deterministic outcome into a stochastic one and may lead to violations of the constraints as now SSB limits may be undercut. Such undercuts can be interpreted as negative (hazardous, harmful) events and will happen with some frequency, in probabilistic terms with some likelihood that may be expressed as P(undercut). As in risk assessment terminology risk is commonly defined as

$$Risk = P(harmful\ event) \times severity \qquad \textbf{(24)}$$

we can see that the likelihood of a hazardous or harmful event is only one of two components. We thus would not merely have to count how often the SSB limit set was undercut but also what the severity of undercutting the SSB limit is (consequence, effect size, costs, etc.). That is not easy to define and derive, respectively. It can be done either in physical or monetary terms (loss function) and in terms of an immediate or a future effect. For now we will ignore this second aspect by keeping the severity term constant and set it to one. We thus calculate

$$Risk = P(lower\ SSB\ limit\ undercut)\ . \qquad \textbf{(25)}$$

An illustrative deterministic example of applying the model

Input data

In order to demonstrate the application of our model, we have purposely chosen to use a relatively simply case in order to foster a better understanding of the theory. We use data derived from a real fishery located on Georges Bank (GB) and in the adjacent Gulf of Maine (GOM) within the western North Atlantic. We limit our consideration to five species, where one species is split into two separate components (stocks). The species and stocks chosen include the haddock, *Melanogrammus aeglefinus* (GB stock), yellowtail, *Pleuronectes ferrugineus* (GB stock), witch flounder, *Glyptocephalus cynoglossus* (GOM and GB combined stock), American plaice, *Hippoglossoides platessoides* (GOM and GB combined stock), and Atlantic cod, *Gadus morhua* (separate GOM and GB stocks). All species/stocks are assessed and managed by the National Marine Fisheries Service (NMFS) located in Woods Hole, MA, USA where GB and GOM witch flounder and American plaice are each managed as one stock. On the other hand, the two cod stocks (GB and GOM) are separately assessed and managed by NMFS; for computational reasons we apply a trick and consider them numerically as being two different species in order to allow a simplified implementation of the bycatch matrix as presented below. Most of the relevant stock data were taken as reported in the Groundfish Assessment Review Meeting (GARM) for year 2005 (NEFSC 2005).

We base our scenarios on a planning horizon (rebuilding period) of 10 years, starting with year 2006. Since our starting point is the year 2006, we took all relevant species related data from the year 2005. All data used are age dissolved consisting of abundance estimates, weight, partial recruitment, and maturity observations. The abundance estimates are based on VPA estimates derived from domestic commercial catch data as well as scientific surveys performed by NMFS. The other data used (weight, maturity, partial recruitment) stem either from market sampling or from previous technical experiments and provided by NMFS researchers (Steven X. Cadrin, personal communication).

The bycatch data used for the bycatch matrix are taken from an industry-based survey performed by the School of Marine Science and Technology (SMAST) (University of Massachusetts, New Bedford, MA, USA) mainly on Georges Bank (Rountree et al. in review). The bycatch data are used to set up a non-symmetric diagonal matrix of technical interactions (see equation (17)) as presented in Table 1. Cell entries consist of normalized fractions of bycatch per each bycatch-species (column) and for each target fishery (row); thus its diagonal contains exclusively ones; its off-diagonal values are larger than zero if technical interactions occur and zero if no interactions occur (in the case of no interactions the matrix is equivalent to a symmetric identity matrix with all off-diagonal values being zero).

As we consider two different cod stocks we have to relax the usual definition of a technical interaction which normally is only applied to different species, and apply it to two different populations herein. As we usually cannot distinguish between individuals of different populations or stocks of one species in the catch, we utilized results from a cod tagging program (see http://www.gmamapping.org/codmapping/20893) to provide us with a proxy estimation. This allowed us to infer a percentage of 1% cod movement from the GOM area into the GB area and of 4% cod movement vice versa (see the two first rows and columns in the bycatch matrix in Table 1). For the purpose of our illustrative example application of our optimization model, we took these fractions as a proxy estimate for the proportion GOM cod in GB cod catches and vice versa. As we have no data on the technically interaction between cod and other species in the GOM area we assumed the values as for the GB area, although we know that this might be unrealistic as the species mix in the GOM area differs from that of the GB area. However, we accept this oversimplification for the purposes of our model illustration.

We used estimated versions of recruitment functions as taken from the most recent GARM report (NEFSC 2005) and shown in Table 2. The SSB rebuilding targets (in tons) to be reached at the end of the 10 years rebuilding period are defined here as species specific biomass reference point estimates (B_{MSY}) again taken from the 2005 GARM report (NEFSC 2005) and shown in Table 3. The lower F limit for the optimization process is set to 0; the upper F limit (see equation (17)) not to be exceeded during the optimization process are represented by F_{MSY} estimates taken from the 2005 GARM report (NEFSC 2005). These F_{MSY} values are provided in Table 4. The values assumed for natural mortality M are also taken from the GARM report and are 0.2 for all species/stocks except for witch flounder which is assumed to be 0.15.

The objective function used here maximizes the overall catch at the end of the rebuilding period and is constrained by rebuilding targets in the following manner:

$$\begin{aligned}
\text{Objective Function} = \text{Total Catch} \quad & - 2.5 \times \max(0, 216780 - SSB_{GB\ Cod}) \\
& - 2.0 \times \max(0, 82830 - SSB_{GOM\ Cod}) \\
& - 3.2 \times \max(0, 250300 - SSB_{Haddock}) \\
& - 3.7 \times \max(0, 58800 - SSB_{Yt\ Fl}) \\
& - 10 \times \max(0, 25248 - SSB_{Wi\ Fl}) \\
& - 2.5 \times \max(0, 28600 - SSB_{Am\ Pl}) \, .
\end{aligned}$$

The six values right after the minus signs are weight factors of the penalty term and are chosen so that the species specific rebuilding target biomass will be reached for certain at the end of the rebuilding period. Selecting these values required some prior experimenting.

Our strategy of optimizing the F values is chosen to be in compliance with the NMFS strategy of "constant F values". That is for each species we optimized only one F value (instead of a set of yearly values simultaneously) and kept this value constant over the entire rebuilding period. The background for this is that

(1) NMFS does not want to control fluctuating F values, but finds it easier to observe and watch one value kept stable over the entire planning horizon

(2) NMFS expects more stable catch values which would be of some advantage for the commercial fishermen as it stabilizes their income.

For all our calculations we used the interactive matrix language SAS/IML (SAS Institute Inc. 1999). We applied the Dual Quasi-Newton Optimization with the Dual Broyden-Fletcher-Goldfarb-Shanno update to our optimization problem in which the gradients are computed by the finite difference method (SAS Institute Inc. 1999).

Results and Interpretation

First of all, the Dual Quasi-Newton Optimization algorithm terminated with a feasible solution for the estimated/optimized parameters (F values) outputting return code (RC) = 5 (FTOL criterion satisfied - relative F convergence) . This means that based on the given data, constraints, and termination criteria no better solution (i.e. no higher total catch) could be found (i.e. achieved) by selecting another set of parameter values (F values) through re-estimation/re-iteration. The optimization results are summarized by the SAS output as follows: "6 parameter estimates, 0 active constraints, 65 iterations, 436 function calls, 162 gradient calls". The final objective function value is given as 516433 (rounded) which is basically the value of the total catch in tons accumulated in time minus the 6 biomass constraints (which in this case all yielded 0 as all goals were met). The accumulated catch numbers per species in tons are (rounded to the nearest integer): 123919 (cod GB), 106285 (cod GOM), 247970 (haddock), 19814 (yellowtail), 8353 (witch flounder) and 10090 (American plaice).

Biological results fro all five species (and six stocks) over the 10 year rebuilding period are shown in Figures 5 and 6. Plotted are SSB, B, C, optimized F values, and derived total F values as well as their associated limits over time (x axis). In all cases, the scaling of the left y axis represents the 3 biomass and catch related variables (SSB, B, C), that of the right y axis is linked to the two F related variables (F, total F). In each panel the two dashed lines without extra symbols assigned are the species related biomass targets ($B_{MSY,}$ long dashes) and the upper F limits (F_{MSY}, short dashes). The other curves and symbols assigned are all explained by the legends on the bottom of the figures. However, it should be mentioned that the two curves for the F variables are assigned the same symbol (a square) to indicate that these are directly linked. To distinguish them we used two different line types: a solid line for the total F, a dashed line with short dashes (but with larger gaps than that for the upper F limit) for the estimated/optimized F values. It can now be seen that

(1) all rebuilding targets in terms of SSB were met and

(2) all total F values were kept below the given limits.

It can be further inferred from both figures that the total F value is always larger than that of the estimated/optimized F variable. This is because of the "hidden" effects due to bycatch of the species of interest in other target fisheries. With the exception of haddock, in all cases B and SSB differ from each other substantially. In the case of haddock, the similarity of the B and SSB curves are a result of the early maturation strategy of haddock. Haddock seems to be also a special case from another point of view: even keeping the F values constant on a very low level leads to a dramatic decrease of the two biomass levels, so that the general trend for both biomass curves is persistently negative. This is different from the pattern all other species show. But, this is also independent from any bycatch issue as a run of the optimization program under the same conditions but with a no-bycatch assumption did not change this pattern for haddock at all. From this we would infer that the upper F limit as stated in the last GARM report (NMFS 2005) is selected too high for haddock as the program selects optimized values that are much smaller than that of the upper F limit (0.07 instead of 0.26). In the case of the no-bycatch scenario the two F curves also fell close together for haddock. It can be furthermore stated that the no-bycatch scenario also led to a somewhat higher overall catch (548001 tons) due to a higher allocation of allowed catches specifically for American plaice. However, the no-bycatch scenario ignores the problem of bycatch completely and is thus not recommended for any decision making procedure.

Although this example was designed to focus on the results of the "constant F value strategy" we additionally wanted to compare the results with that of a "flexible F value strategy". This strategy allows annually changing F values to be selected. Our "flexible F value" scenario shows that this catch tactic could improve the overall catches by 8.31%: the total catch accumulated over all species and years yielded 559365 tons which is 42931 tons more than with the "constant F value strategy". Looking at the species disaggregated catches indicates that specifically the allowed haddock and yellowtail flounder catches become substantially larger than compared with those of the "constant F strategy" and thus could be significantly optimized. We also performed the "flexible F value strategy" based on a no-bycatch assumption. As before under the "constant F strategy" this scenario led to a further increase of an allowed total catch (637277 tons) being equivalent to a 12 % rise - mainly due to an allocation of higher haddock, yellowtail flounder, witch flounder, and American plaice catches. The steepest increase was for American plaice yielding to catch four times higher catch than with the bycatch scenario. This is due to higher F values being directly and exclusively allocated to the individual target fisheries during the optimization process as these are uncorrelated under the no-bycatch assumption. But again, the no-bycatch scenario ignores the problem of bycatch completely and is thus not recommended for any decision making procedure.

Discussion

Our study differs from most previous approaches which were usually focused on single species and lacked a broader rebuilding framework. It is thus quite different from conventional procedures of obtaining a sustainable fishery such as single species MSY concepts. In contrast our approach explicitly states a control variable (here fishing mortality or fishing effort) that will be optimized during the process within *a priori* specified upper and lower limits. It does this by maximizing an objective function that consists of either biological or economical yields (or profit). This yield (or profit) can be constrained by conditions such as the match of rebuilding targets, bycatch, as well as by quota restrictions. Even stability aspects either in the catches (e.g. restricted deviation from a desired or nominal value such as the average catch during the entire rebuilding period) or in quota changes (e.g. the TAC should not vary of, for instance, for more than 15% from year to year to ensure stability) can be integrated in our optimization model. This approach has been adopted from economic (econometric) control theory where it is usually applied in controlling a business, company, or a national economy using a set of instrument variables. The heart of this approach is a non-linear optimization algorithm that outputs the optimal set of parameter values - in this case values of the control variable fishing mortality or fishing effort for the planning horizon. A second core feature is the integration of technical interactions by integrating a matrix of technical interactions between core species. We show in a demonstration example how this can be done using a bycatch matrix for six populations and five species, respectively. This matrix can be easily extended to incorporate fleets, segments, metiérs, or other management units. It can also make use of spatial or tagging information. This makes our optimization model framework a general and very flexible framework in which the varying biological or economical information sources and modules, respectively, can by easily replaced or extended by alternative or additional information sources or submodels.

Thus, based on the availability of data this framework allows the flexibility of specifying:

(1) the species incorporated
(2) stocks/populations incorporated
(3) areas incorporated
(4) the type of the R-SSB relationship used
(5) the length of the planning horizon
(6) the penalty terms
(7) the constraints such as
    a. using effort or fishing mortality
    b. defining their lower and upper size limits
    c. defining the maximization criterion (physical catch, monetary catch, profit, etc.)
    d. defining the weighting of the components in the maximization criterion.

We consider our stock rebuilding approach as an adaptive dynamic framework that is modular in construction and subject to further improvement as our knowledge increases. However, the primary reason we use this approach is to provide an alternative for specifying a medium to long-term management strategy to the ad-hoc techniques often used in the past. For example, conventional techniques are often applied in equilibrium settings and relate to maximizing production, Y/R or SSB/R, although we do not know whether the stocks of concern are really in an equilibrium state. In addition conventional techniques or "management algorithms" are also not always consistent with the data and information at hand.

Traditionally stock assessment techniques have been developed in a single-species setting even though many fisheries take many species simultaneously, except for MSVPA (which still plays a subordinate role). But even in a single species setting, the conventional techniques leave much to be desired. This is because these techniques do not always yield a clearly defined maximum or optimum. Our approach is intended not only to accounting for multiple-species interactions, but to develop a consistent framework with clear optimality, while at the same time taking into account the high variability in fisheries data (as the approach allows for the use of stochastic rather than deterministic functions in association with a bootstrapping method).

However, although we base our approach on the best knowledge we have so far, this knowledge is not perfect and can be expected to change over time. Our modular model approach allows us to incorporate these changes, for instance, by replacing some of the model equations with better fitting ones. We furthermore may have to improve our empirical knowledge in important key areas and therefore carry out more detailed experiments/surveys/analysis of existing data regarding the following issues:

(1) interactions:
    a. biological: analysis and modeling of multi-species interactions based on food habitat of groundfish species

b. technical:
   - development of better methods to quantify bycatch and discards
   - modeling the impact of discards on the Georges Bank food web

c. environment: analysis and modeling of species-environment interactions

(2) analysis and modeling of stock-recruitment relationships and their interlink to other biotic and abiotic factors

(2) fish distribution:

a. analysis of fish distribution patterns as they relate to habitat and environmental factors and how distribution affects stock assessment

b. analysis of regional migratory patterns

(3) more detailed interpretation/analysis of hydroacoustic data.

Apart from whether this biological knowledge is available or not, the concept of the rebuilding framework does in principle incorporate modifiable functions, vectors and matrices addressing all the points above ("placeholders"). The required information must "only" be determined and thus filled in.

For instance, if we have more detailed information about migration patterns, for instance, by using digital storage tags and geolocation methods (see Gröger *et al.* 2005a, in review), the spatial component could be easily implemented by either introducing a migration matrix or by modifying the matrix of technical interactions (i.e. the bycatch matrix). Or, if we have better information about predator-prey relationships using, for instance, stomach content investigations, we might be able to set up a matrix of biological interactions similar to the bycatch matrix where the columns are represented by the prey species and the rows by the predator species. This matrix could then be multiplied with an M vector (a vector of either assumed or given "default" or "residual" natural mortalities) in a similar fashion as that what we have done with the bycatch matrix and the optimized F vector using equation (17).

Regarding our illustrative application of the model to the Georges Bank groundfish fishery: this simplified example shows how to alternate options as well as conditions and find out what the best strategy could be by comparing the outcomes. However, because parameter estimates are based on data (i.e. incomplete information) as well as on the functional form chosen, this relies on the assumption that the functional form, data and parameter estimates are correct. We thus could question whether specific parameter estimates and functions are right under all conditions. Hence, for verification purposes some kind of uncertainty could be implemented as part of the optimization algorithm, for instance, by adding some noise terms to the biological functions build in. Bootstrapping could then help to derive expected values and ranges of the optimized parameters (F, F_{tot}) as well as their effect on dependent quantities (biomass, catch) in terms of lower/upper bounds, variances, biases, etc..

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Review Meeting (GARM) 2005 data on groundfish population and fishery data used as input to our optimization procedure. We would also like to thank Steven X. Cadrin, CMER director (NMFS/UMassD), for thoroughly discussing with us the optimization strategy preferred by NMFS and for his idea to make use of the cod tagging data by incorporating them into the matrix of technical interactions (bycatch matrix).

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Table 1. Matrix of technical interactions among species and stocks used in the optimization model illustration for the Georges Bank groundfish fishery, based on data derived from an industry based trawl survey (Rountree et al. in review).

	bycatch species					
Target fishery	cod (GB)	cod (GB)	haddock	yellowtail	witch flounder	American plaice
cod (GB)	1	0.04	0.13	0.04	0.07	0.03
cod (GOM)	0.01	1	0.13	0.04	0.07	0.03
haddock	0.26	0.01	1	0.05	0.07	0.07
Yellowtail	0.12	0.01	0.04	1	0.02	0.03
witch flounder	0.48	0.02	0.06	0.03	1	0.14
American plaice	0.16	0.01	0.1	0.02	0.34	1

Table 2. Estimations of recruitment functions for species and stocks used in the optimization example for the Georges Bank groundfish fishery, based on data provided in the most recent GARM report (NEFSC 2005). R is expressed for age 1 in thousands, except for witch flounder which is for age 3.

Species/stock	Recruitment
cod (GB)	R=58569.90 x SSB/(182740.90 + SSB)
cod (GOM)	R=9854.36 x SSB/ (7516.10 + SSB)
haddock	if SSB < 75000 t then R=9879 else R=10615
yellowtail	if SSB < 5000 t then R=13220 else R=24444
witch flounder	Mean R=32549.5
American plaice	Mean R=8813

Table 3. Rebuilding targets for species and stocks used in the optimization model illustrative example, based on data obtained from the most recent GARM report (NEFSC 2005).

Species/stock	Target (in tons)
cod (GB)	216780
cod (GOM)	82830
haddock	250300
yellowtail	58800
witch flounder	25248
American plaice	28600

Table 4. Upper F limits, represented by F_{MSY} values obtained from the most recent GARM report (NEFSC 2005) that were used in the optimization illustration for the Georges Bank groundfish fishery.

Species/stock	F_{MSY}
cod (GB)	0.175
cod (GOM)	0.225
haddock	0.263
yellowtail	0.25
witch flounder	0.23
American plaice	0.166

Figure captions

Figure 1: Conventional stock assessment and management procedure.
Figure 2: Simplified catch-effort diagram for deriving MSY related quantities and proxies (MSY = maximum sustainable yield, F_{MSY} = fishing mortality at MSY, B_{MSY} = biomass at MSY, B_{PA} = precautionary approach reference point for biomass, B_{lim} = limit reference point for biomass).
Figure 3: Graphical presentation of the algorithmic rebuilding philosophy (DAS = days-at-sea).
Figure 4: Layout of the structure of the non-linear optimization algorithm showing the linkages between the various model equations as they appear in the body of the text. The illustration of the layout is based here on a simplified two-species-two-areas example and a 10-years planning horizon for which the objective function is to be optimized.
Figure 5: The three panels display the temporal trajectories for biomass (B, SSB), catch C, fishing mortality (F, F_{tot}), and recruitment R regarding the three cod and haddock stocks. In all cases, the left y axis represents the three biomass and catch related variables (SSB, B, C), the right y axis the two F related variables (F, total F). The two curves for the F variables (F, F_{tot}) are assigned the same symbol (a square) to indicate that these are directly linked to each other. To distinguish them two different line types were used: a solid line for F_{tot}, a dashed line with short dashes for the estimated/optimized F values. The two dashed lines with no extra symbols are the species related biomass targets ($B_{MSY,}$ long dashes) and the upper F limits (F_{MSY}, short dashes). All other curves and symbols are directly explained by the legends on the bottom of the figure.
Figure 6: Same description as under Figure 5, but related to the three flatfish species yellowtail flounder, witch flounder and American plaice (see caption of Fig. 5).

Figures

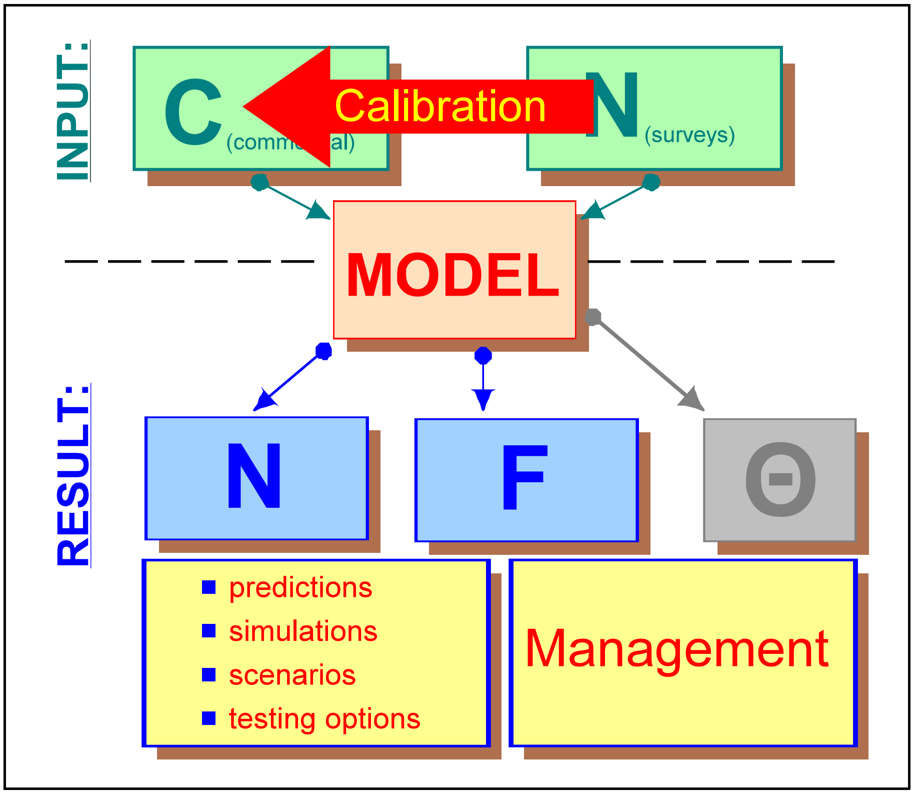


Fig. 1

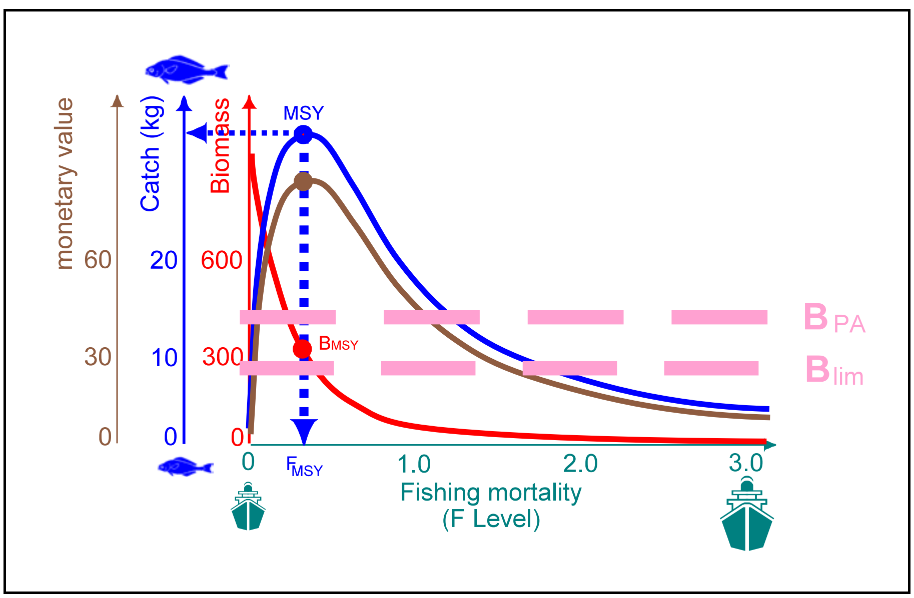
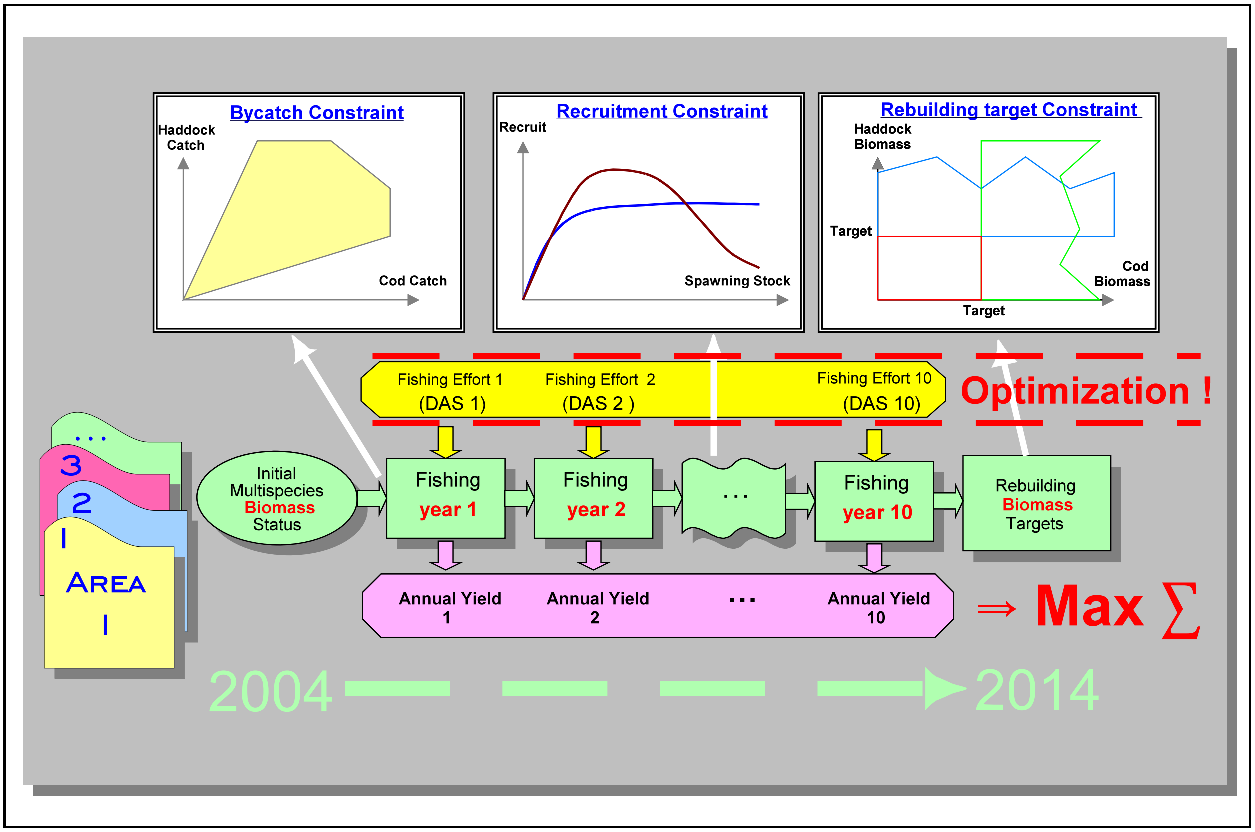


Fig. 2


Bycatch Constraint
Haddock Catch
Cod Catch
Recruitment Constraint
Recruit
Spawning Stock
Rebuilding target Constraint
Haddock Biomass
Target
Cod Biomass
Target
Fishing Effort 1 (DAS 1)
Fishing Effort 2 (DAS 2)
Fishing Effort 10 (DAS 10)
Optimization !
...
3
2
1
AREA 1
Initial Multispecies Biomass Status
Fishing year 1
Fishing year 2
...
Fishing year 10
Rebuilding Biomass Targets
Annual Yield 1
Annual Yield 2
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Annual Yield 10
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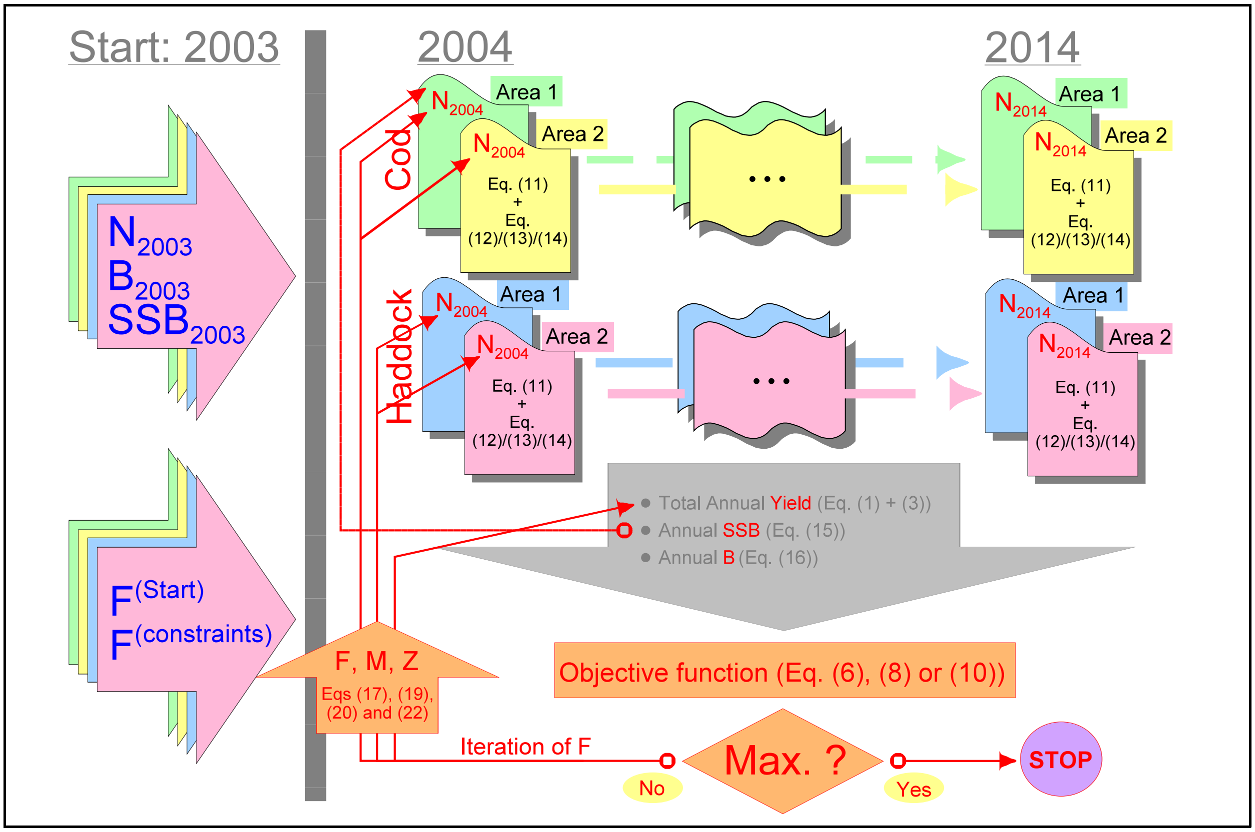
2004
2014

Fig. 3


Start: 2003
2004
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N2003
B2003
SSB2003
F(Start)
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Haddock
N2004
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• • •
Total Annual Yield (Eq. (1) + (3))
Annual SSB (Eq. (15))
Annual B (Eq. (16))
F, M, Z
Eqs (17), (19), (20) and (22)
Objective function (Eq. (6), (8) or (10))
Iteration of F
No
Max. ?
Yes
STOP

Fig. 4

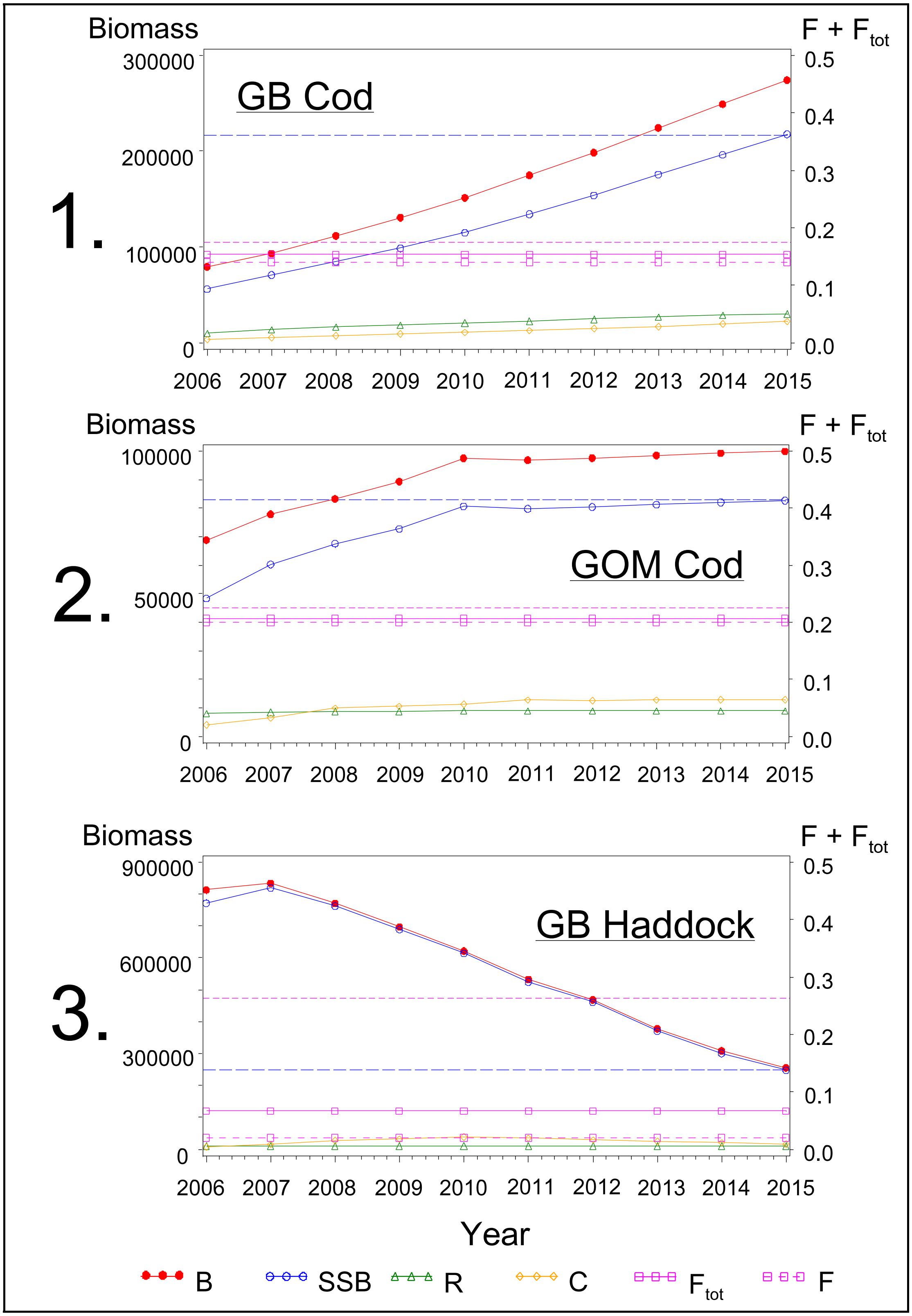
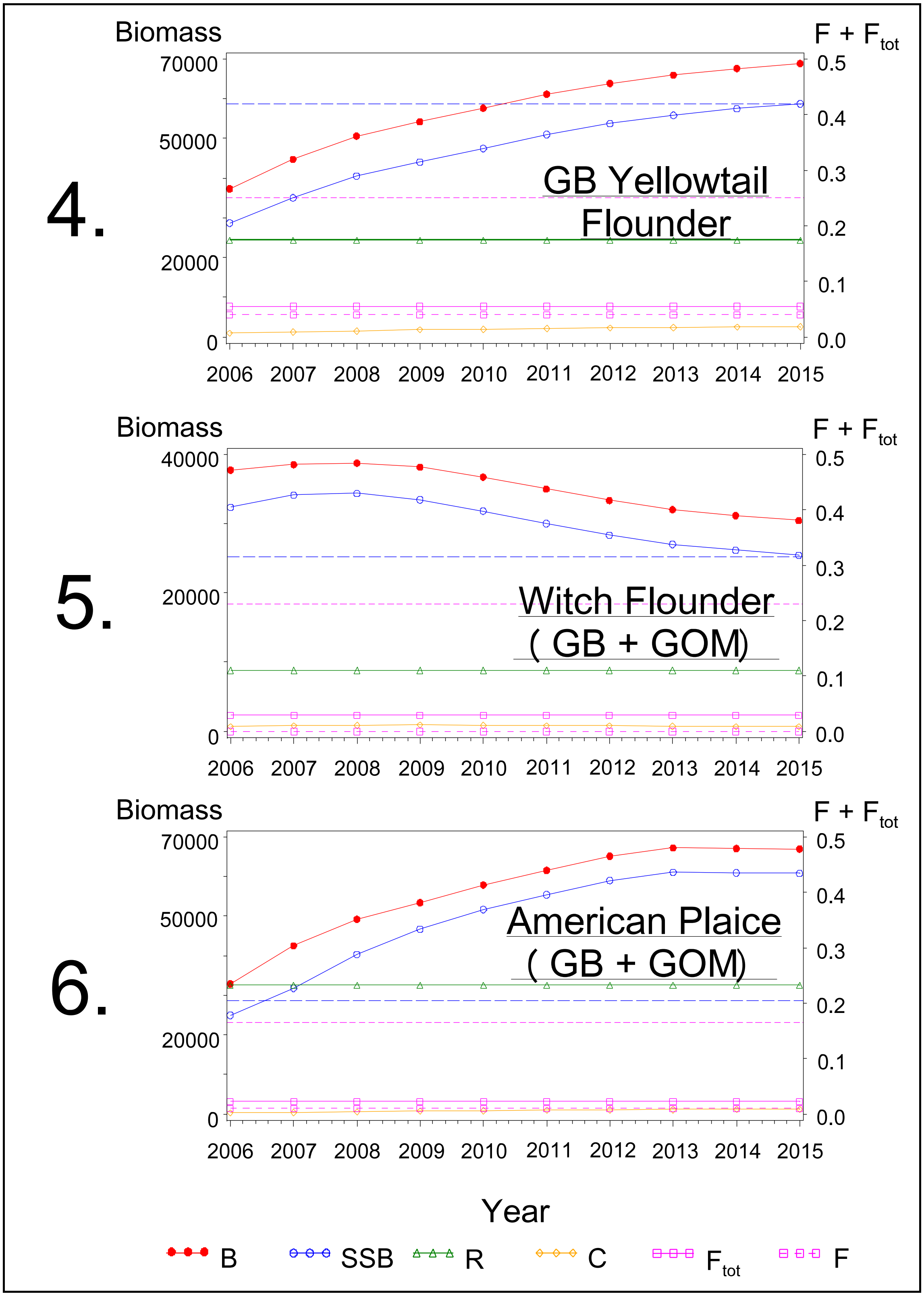

Biomass
F + F tot
GB Cod
1.
GOM Cod
2.
GB Haddock
3.
Year
B
SSB
R
C
F tot
F

Fig. 5



4.
Biomass
F + F_{tot}
70000
50000
20000
0
0.5
0.4
0.3
0.2
0.1
0.0
GB Yellowtail Flounder
2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
5.
Biomass
F + F_{tot}
40000
20000
0
Witch Flounder (GB + GOM)
2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
6.
Biomass
F + F_{tot}
70000
50000
20000
0
American Plaice (GB + GOM)
2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
Year
B
SSB
R
C
F_{tot}
F

Fig. 6

Annex to the 2006 Report of the ICES Study Group on Risk Assessment and Management Advice (SGRAMA)

Management advice accounting for model uncertainty

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Introduction

Advice to fisheries managers regarding quotas (TACs) is currently based on a series of essentially deterministic calculations. Firstly, one assessment model (out of many possible such models) is selected that experts think is the “best”, in some sense. Secondly, the population is rolled forward into the intermediate and quota years, using assumptions about recruitment, growth and exploitation. Finally, the quota advice is based on the forecasted landings that result in desirable outcomes for fishing mortality, stock biomass, or both. All three stages are deterministic in the sense that they use only one out of many possible realisations of the assessment and the forecast.

One consequence of this is that the quota advice is very sensitive to the large number of assumptions that are made during this process. Furthermore, many of these assumptions do not have a strong scientific justification, and may instead be based on the tradition within a particular assessment working group, or the intuition of whichever scientist argues the most cogently. This leads to advice which is pretending to be exact (in that a single number is given as the quota), but which can in fact be extremely uncertain.

A better approach might be to incorporate explicitly the uncertainty in the assessment and forecast process. Rather than a single “best” assessment, managers would be presented with a distribution of possible assessments. On the basis of these distributions, managers would be able to determine the *probability* of biomass or mortality being above or below defined reference points. Each of these possible assessments would then be rolled forward in time in forecasts which would incorporate uncertainty about recruitment, growth and exploitation, and under different scenarios about quotas. The outcome would be a diagram summarising the probability (as a percentage) of biomass being below Blim or Bpa, or mortality being above Flim or Fpa, for a range of different quotas. It would then be for managers to decide what level of risk they would be willing to accept, and determine quotas accordingly: or the risk level might be built in to management agreements and harvest control rules, thus simplifying much of the advisory process.

Methods

An analysis of model uncertainty requires a framework within which many candidate assessments and forecasts can be carried out quickly and efficiently. For this purpose I have used the FLR system (http://www.flr-project.org/doku.php) under development in the EU EFIMAS-COMMIT-FISBOAT cluster. FLR consists of a number of data classes and methods coded in the R language (R Development Core Team 2005). A simple R script loops over all possible combinations of different XSA settings (Darby and Flatman 1994), running XSA and generating short-term forecasts (with quota constraints) for each one. The following list shows the settings used for the North Sea haddock example (the baseline settings is highlighted in **bold**):

1. F shrinkage = (0.5, 1.0, 1.5, **2.0**)
2. Catchability (q) plateau = (**2**, 3, 4)
3. Plus-group age = (5, 6, **7**)
4. All possible combinations of surveys: for example, with three surveys, the combinations are (1), (2), (3), (1,2), (2,3), (1,3), (**1,2,3**).

It should be noted that the current FLR implementation of the short-term forecast allows for quota (TAC) to be constrained in the intermediate year (i.e. the year immediately after the final year of the historical assessment), not the quota year which is two years after the final historical-assessment year. This needs to be rectified in future versions.

Results

The approach was applied to the 2005 assessment of North Sea haddock, and is summarised in Figures 1–7. The model uncertainty for this assessment is quite high, and certainly encompasses the range of assessments and forecasts that have been the source of much argument and confusion over the past two years. One way to use these results would be to determine (from Figure 6) what TAC in 2005 would give a <10% probability of biomass being less than B(pa) in 2006 – in this example the answer is around 60000 tonnes. From Figure 5 we can also see that the fishing mortality implied by this quota is unlikely to be greater than 0.3.

Discussion

This method is still in the early stages of development, and needs to be explored further. For example, uncertainty in growth and recruitment is not yet incorporated. There is no account taken of parameter estimation uncertainty, and we have restricted the approach to a single assessment method (XSA) when it would be more appropriate to look at several. It may also be appropriate to weight the contributions of different parameters settings to the overall distributions. For example, although choosing F shrinkage in XSA is arbitrary to a certain extent, experience has shown that a low number (0.5) is more likely to induce biased advice than a high number (2.0) in a situation where there is a trend in mortality. These aspects have to be addressed by assessment Working Groups, but the general *approach* shows promise in allowing managers to evaluate the risk associated with their actions. It will also assist assessment WGs – once the range of settings and models to be scanned is decided, the issue of which is the "best" model no longer arises.

References

Darby, C. D. and S. Flatman (1994). 'Lowestoft VPA Suite Version 3.1 User Guide'. MAFF: Lowestoft.

R Development Core Team (2005). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

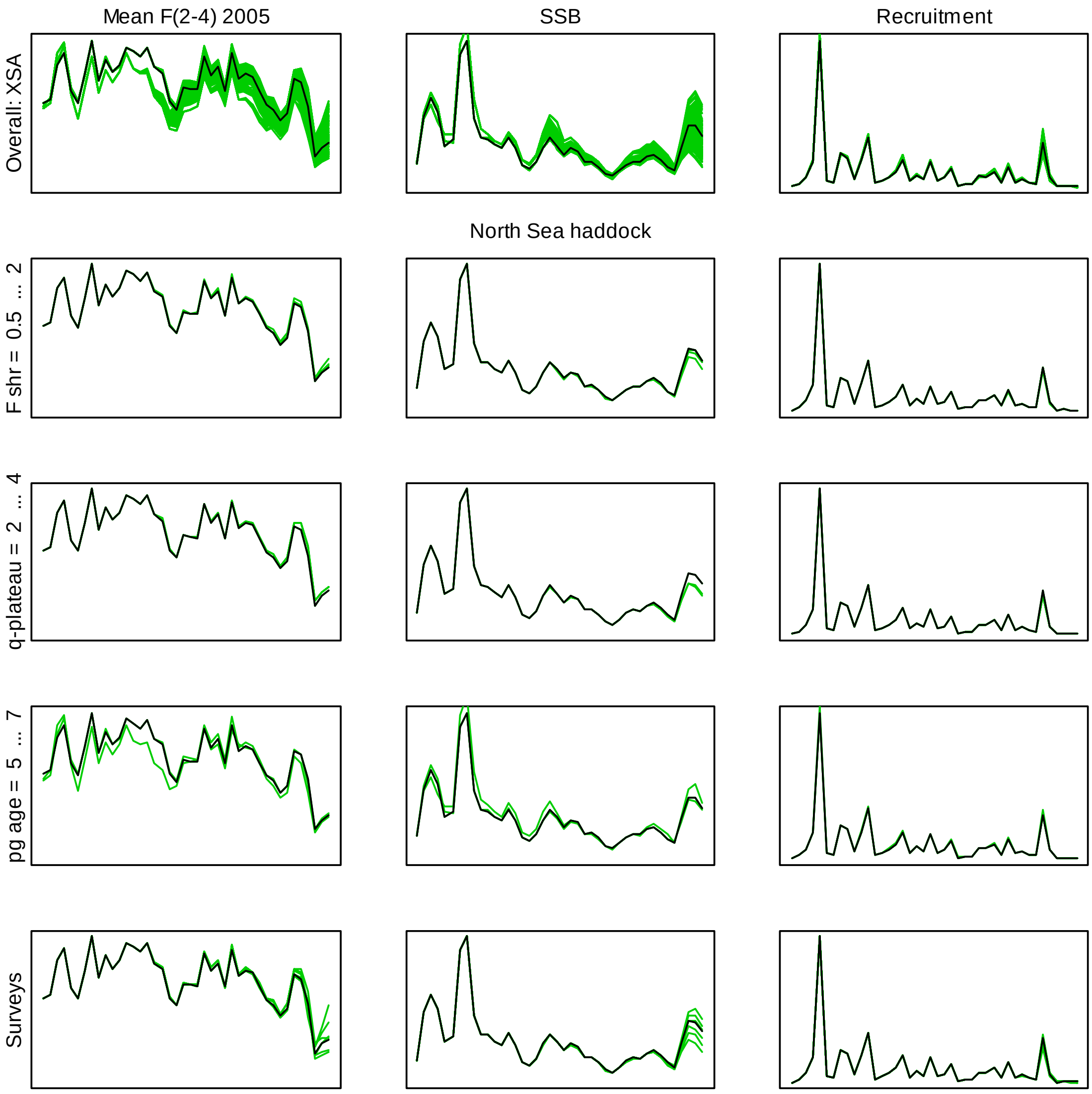

Figure 1: North Sea haddock. Time-series plots showing the effect on the assessment of varying user-defined XSA run settings. The black line shows the baseline assessment from WGNSSK.

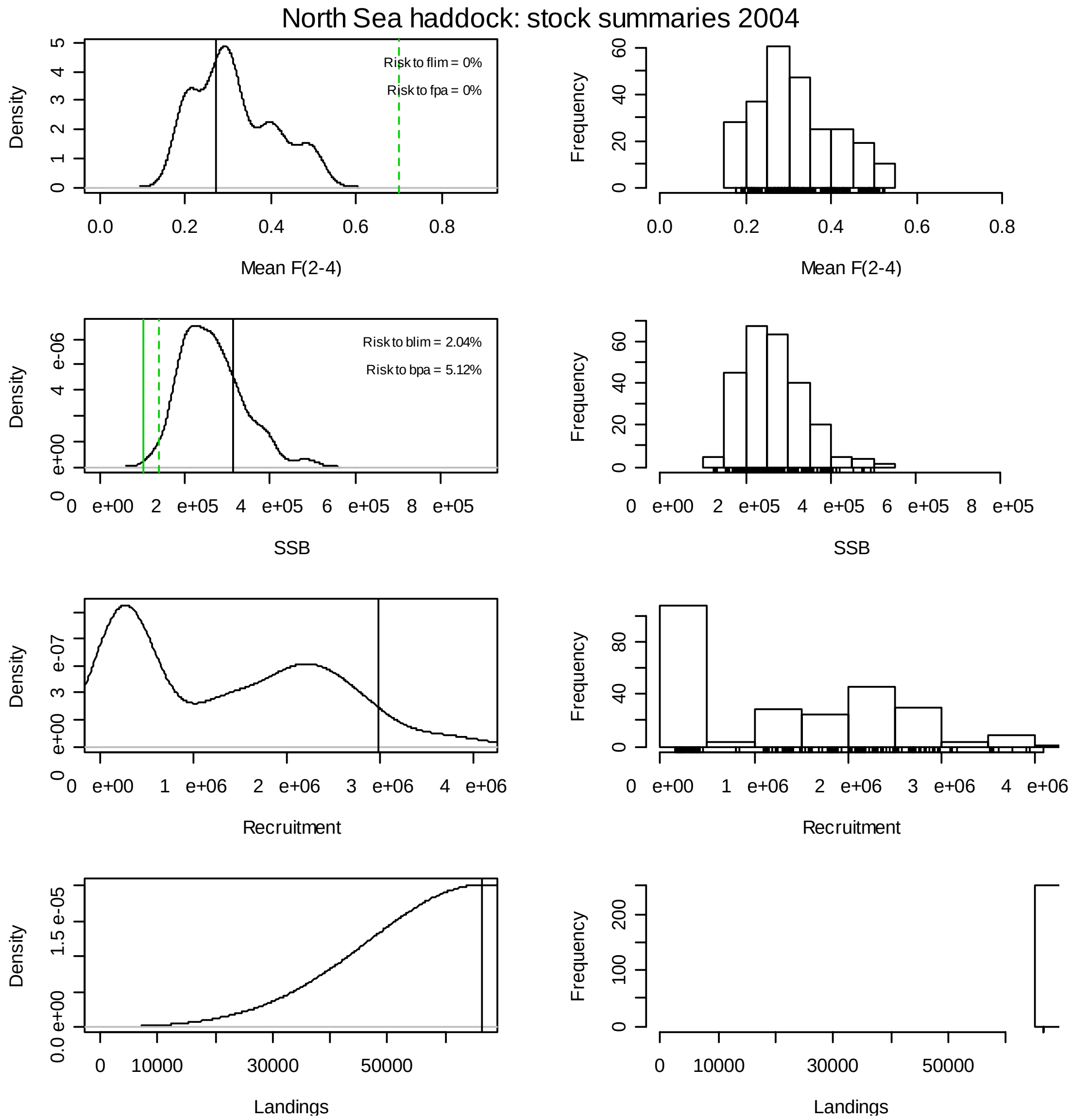

Figure 2: North Sea haddock. Summary of distributions of assessment estimates in the final assessment year (left: density plots, right: histograms). Green vertical lines show reference points, black vertical lines show the baseline assessment. The estimated probability of being above F-reference points (and below biomass reference points) is also given.

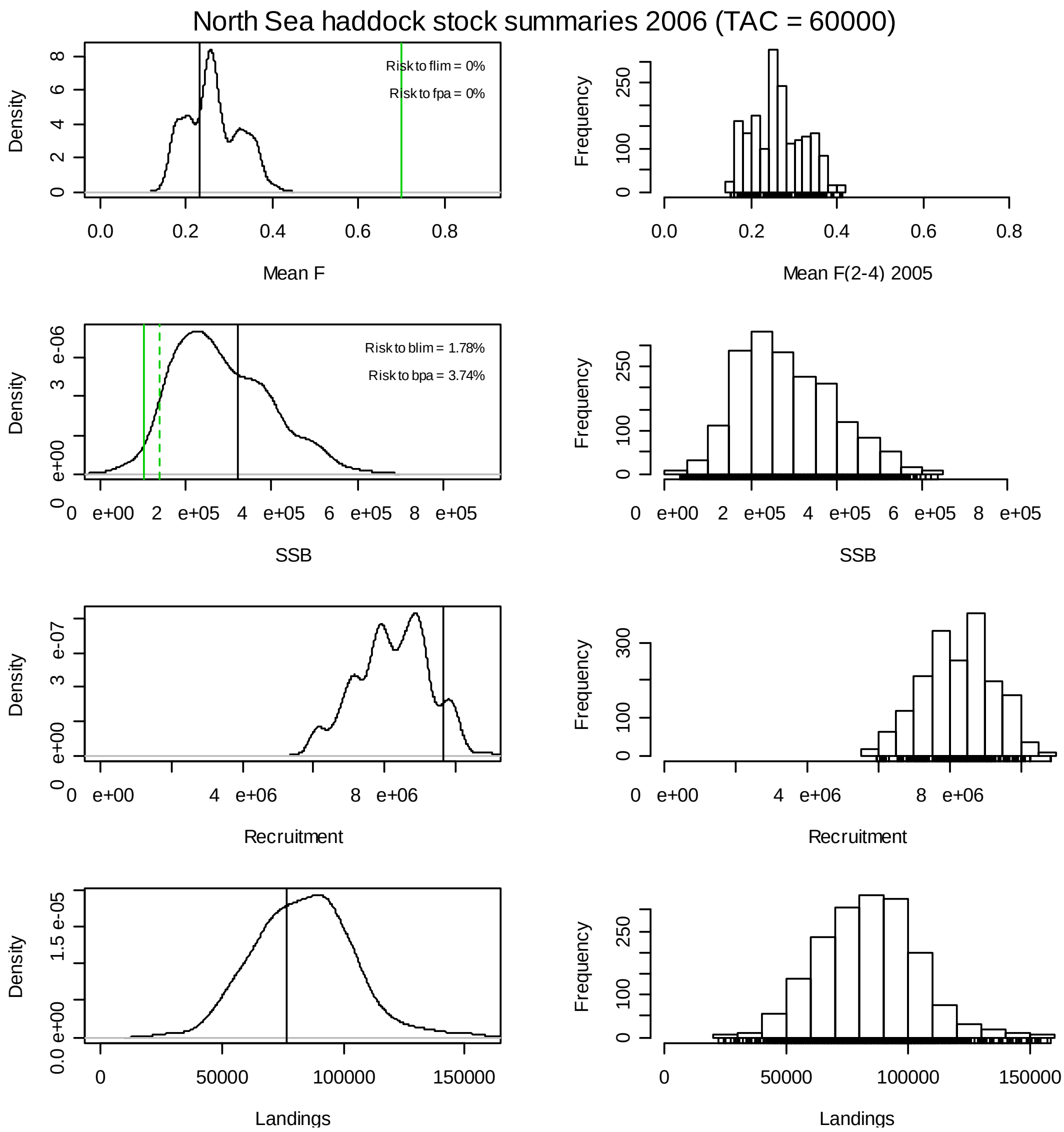

Figure 3: North Sea haddock. As for Figure 2, but for the quota year (two years after the final historical assessment year) and assuming a TAC in 2005 (the intermediate year) of 60000 tonnes.

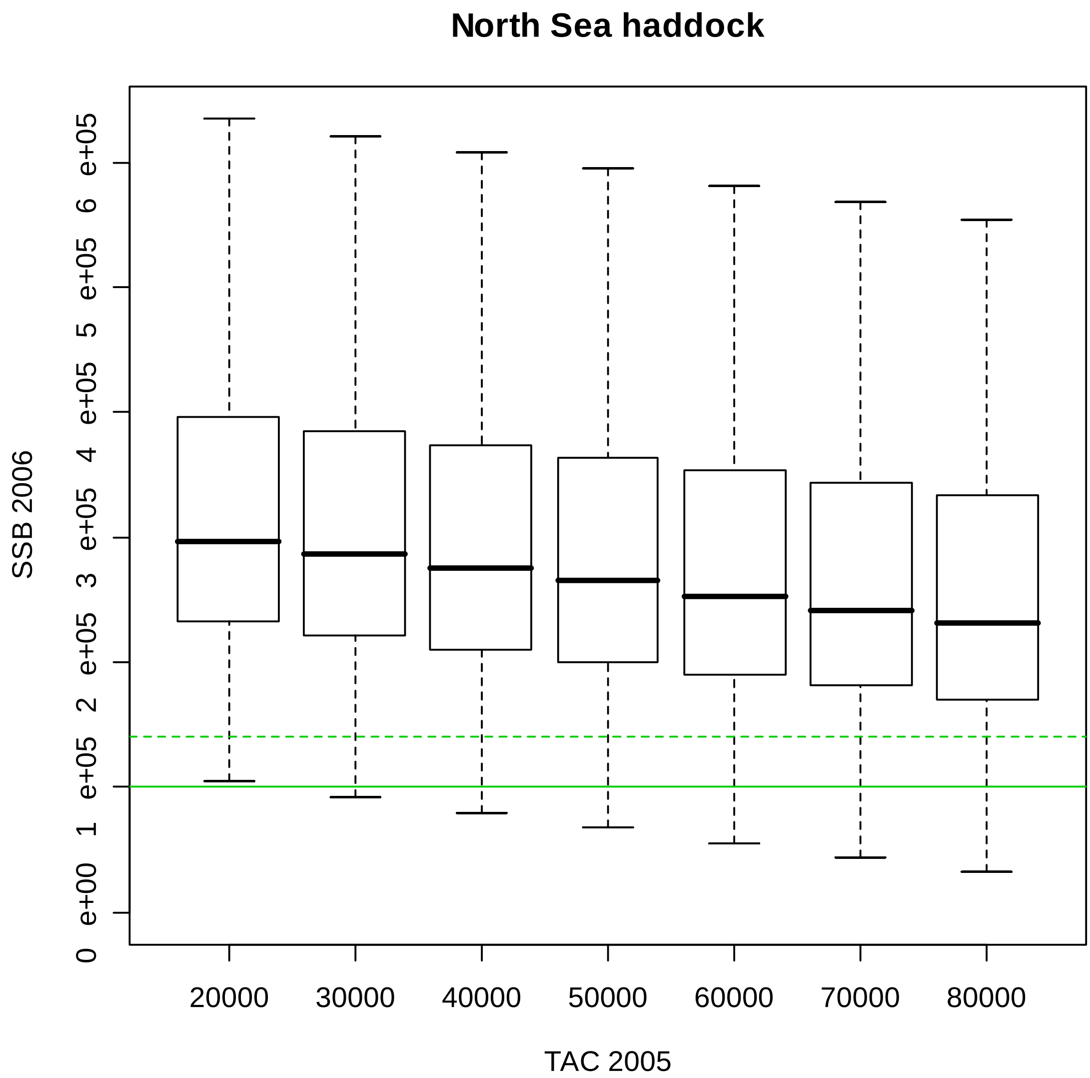

Figure 4: North Sea haddock. Box-and-whisker plots summarising the distributions of forecast SSB in 2006 contingent on different quotas (TACs) in 2005. Green lines show reference points. In each box, the thick line gives the median of the distribution, the top and bottom of the box give the 25% and 75% quantiles, and the whiskers indicate the extent of outliers.

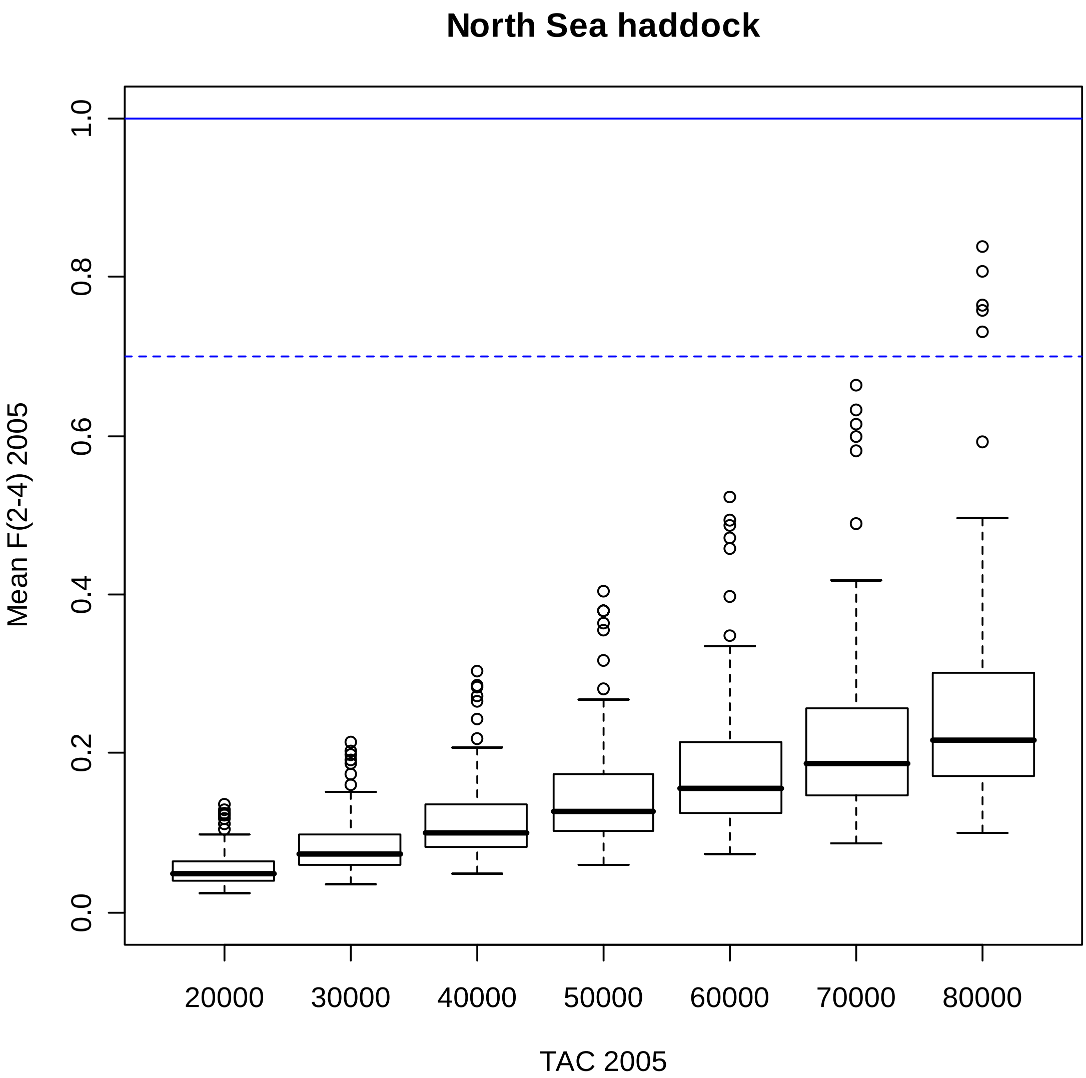

Figure 5: North Sea haddock. Box-and-whisker plots summarising the distributions of forecast fishing mortality in 2005 implied by different quotas (TACs) in the same year. Green lines show reference points. In each box, the thick line gives the median of the distribution, the top and bottom of the box give the 25% and 75% quantiles, and the whiskers and small circles indicate the extent of outliers.

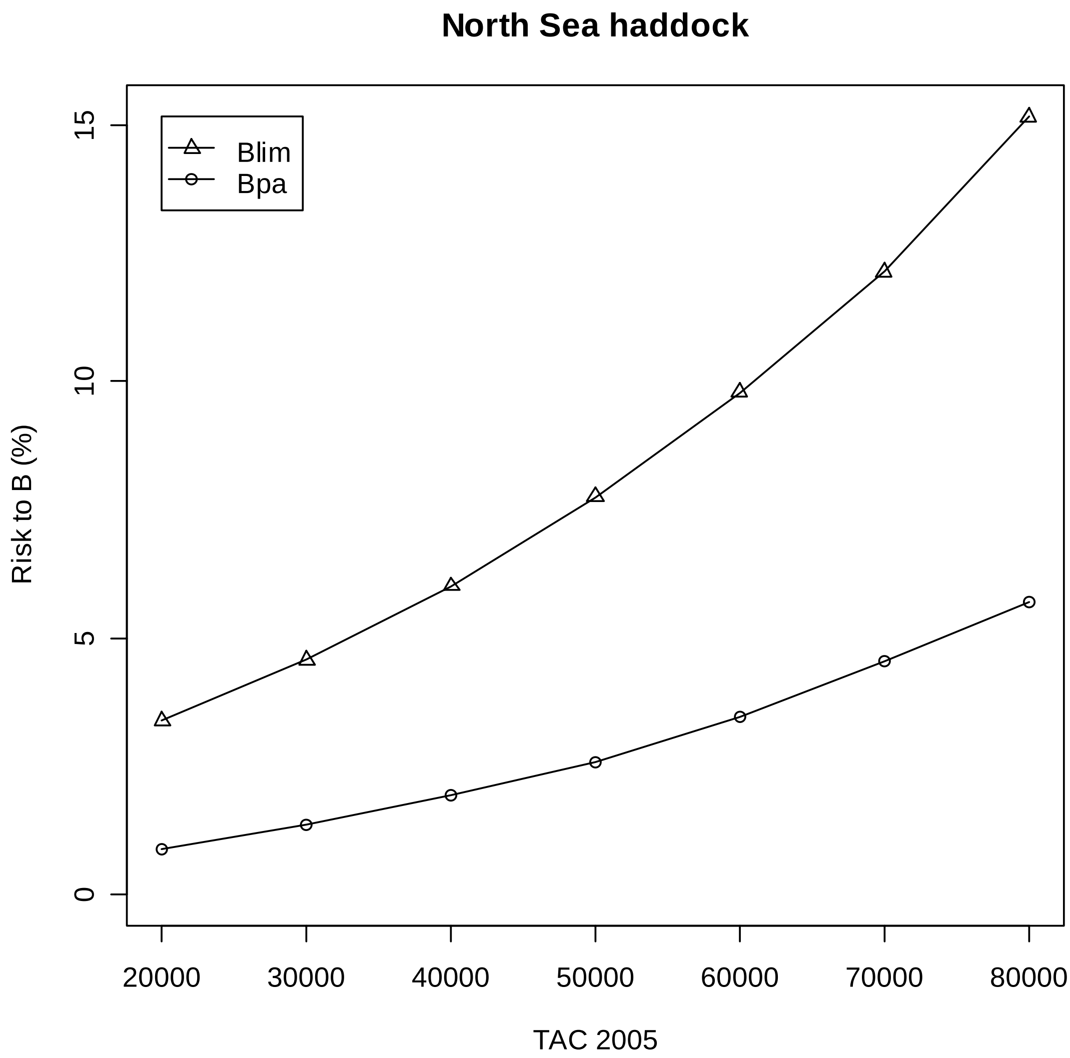

Figure 6: North Sea haddock. The risk of biomass in 2006 being below B(pa) (triangles) or B(lim) (circles) for different TACs in 2005. Note that the legend in the key on the plot is incorrect.

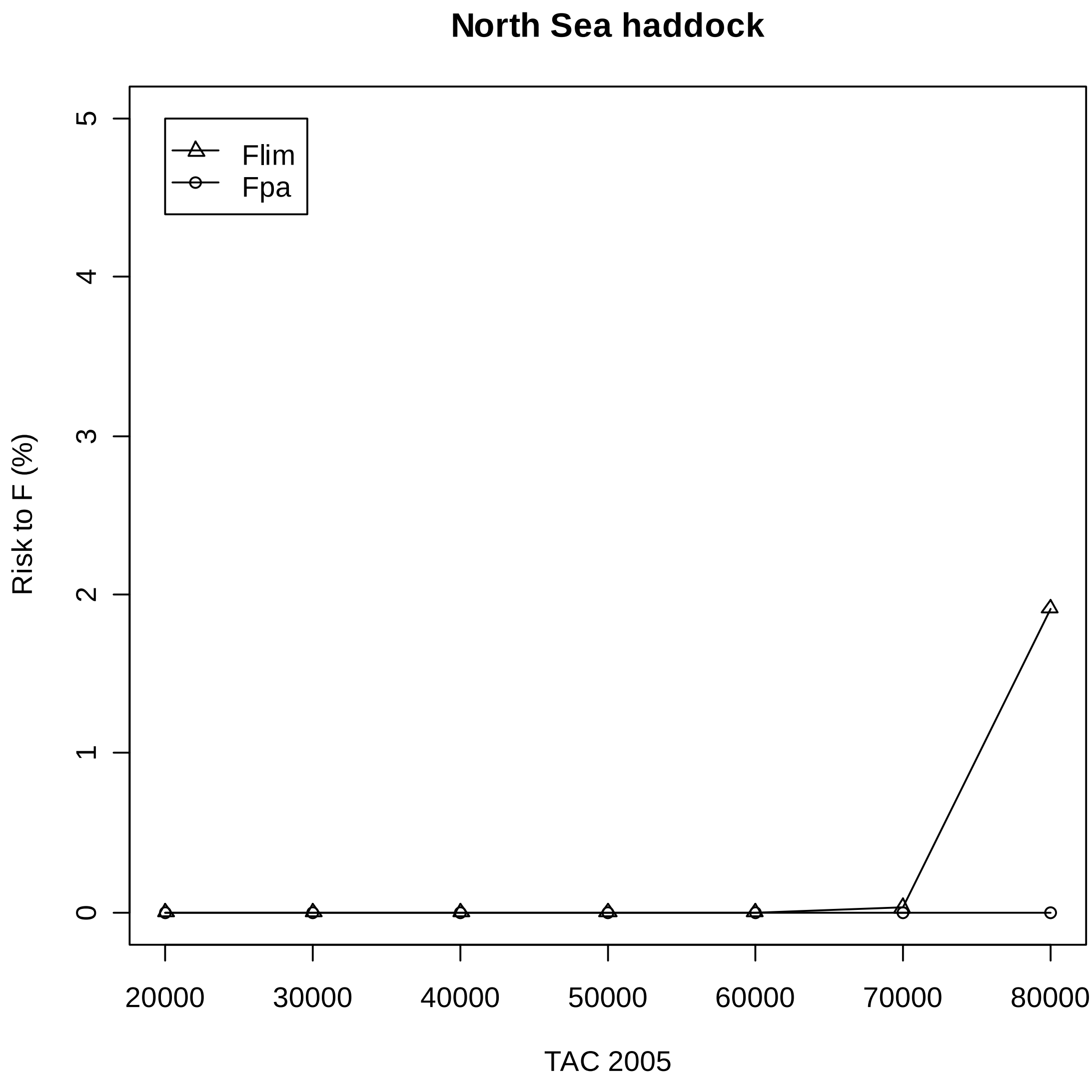

Figure 7: North Sea haddock. The risk of fishing mortality in 2005 being above F(pa) (triangles) or F(lim) (circles) for different TACs in 2005. Note that the legend in the key on the plot is incorrect.